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Performance Study for Inlet Installations

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PREFACE

This report was prepared by McDonnell Aircraft Co. (MCAIR) for NASA Langley Research Center, Hampton, Virginia under contract No. NAS1–19462, entitled "Performance Study For Inlet Installations".

Ms. E. Ann Bare was the program monitor for NASA–Langley Research Center. Mr. Donald C. Bingaman was program manager at MCAIR.

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SUMMARY

A conceptual design trade study was conducted by McDonnell Aircraft Co. (MCAIR) and NASA Langley Research Center to determine the impact of inlet design features incorporated for reduced detectability on inlet performance, weight, and cost, for both fighter and attack-type aircraft. Quality Function Deployment (QFD) techniques were used to prioritize trade study issues, and select "best" air induction system configurations for each of two notional aircraft, the Multi-Role Fighter (MRF) and the Advanced Medium Attack (AMA) bomber. These selections were not driven solely by performance, but were strongly influenced by radar cross section, weight and cost considerations. Both selections provided the lowest air vehicle Takeoff Gross Weight (TOGW). Database deficiencies discovered in the trade study process were identified, and technology roadmaps were developed to address these deficiencies. Two particularly significant deficiencies noted were the lack of a parametric, generic integrated airframe/inlet aerodynamic database for low observable-configured aircraft, and the lack of a broadly applicable and available radar cross section database for trading engine front frame performance against subsonic diffuser obscuration or material selection. Two full configuration Computational Fluid Dynamic (CFD) solutions were completed for the selected configurations to insure the viability of their basic aerodynamic designs, using large multi-block computational structured grids, and a time-dependent Reynolds-averaged Navier-Stokes code. Finally, wind tunnel test plans and two highly parametric, integrated inlet wind tunnel model concepts were developed for follow-on wind-tunnel investigations.

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1.0 INTRODUCTION

The development of survivable, affordable, high performance fighter and attack aircraft is fundamentally dependent on the successful trade of important design features to meet detectability, mission performance, maneuverability and life cycle cost requirements. These trades can be difficult to accomplish because these requirements emphasize different aspects of the aircraft. The deployment of lethal surface-to-air (SAM) and air-to-air missile threats, has placed a premium on reducing aircraft detectability, particularly in radar cross section (RCS), and infrared signature (IR). Future U.S. fighter and attack aircraft will be tasked to perform missions within range of threat warning and tracking radars, and accompanying SAM sites, and thus will be required to have RCS signatures well below those of current aircraft to survive. The three primary drivers of aircraft nose RCS signatures are the avionics apertures (radar, etc.,), the cockpit enclosure and the aircraft inlets. Aircraft detectability and survivability is fundamentally dependent on how much the impact of these contributors can be reduced.

At the same time, the development of agile threat fighter aircraft indicates that while low RCS is necessary, it is not in itself sufficient to guarantee survivability. Air superiority over advanced threat fighters may require agility beyond current U.S. fighter capabilities, and into the Post-Stall (PST) regime. Post-Stall maneuverability requires low speed Angle-of-Attack (AOA) and Angle-of-Sideslip (Beta) capabilities well beyond those of current U.S. fighters. In order to achieve these extreme conditions (60°-90° AOA at 250 knots), inlets must reliably provide low distortion airflow to the engine to allow continuous thrust production for sustained flight and control.

For advanced USN fighter and attack aircraft, carrier suitability poses unique challenges which place special design emphasis on static and low speed inlet operation. Future USN attack aircraft will be designed to carry large loads of ordnance and fuel over hundreds of nautical miles, to allow the carrier strike force to hit potential threats anywhere on the face of the earth. The propulsion system for twin-engine aircraft must be sized to allow safe carrier launch and recovery, given one engine out. A primary Figure-of-Merit, Single-Engine Rate-of-Climb (SEROC), is a function of aircraft thrust/weight, which is in turn proportional to the inlet recovery, (PT2/PT0). Safe operation is also dependent on good inlet/engine compatibility.

For both USAF and USN fighter and attack aircraft, reductions in the number of friendly airfields, combined with declining defense and aircraft procurement budgets, require that affordable fighter and attack aircraft designs be produced with longer range and greater payload capabilities than the aircraft they will replace. Keys to achieving these goals are aerodynamic lift/drag characteristics, and more efficient propulsion systems. Propulsion system performance, is determined, in part, by the inlet recovery, inlet induced drag, and the engine operating characteristics, which can be adversely affected by high inlet distortion and turbulence.

Divergent airframe requirements result in a large set of conflicting inlet design requirements which must be balanced to allow design convergence on to successful concepts, Figure 1. Design integration issues drive the inlet to lightweight, low volume geometries which minimize or eliminate anti-icing and present minimum interference with stores or landing gear. Low RCS inlet aperture design requires long, aligned, in-plane and sharp edges and 100% line-of-sight (LOS) blockage of the engine fan rotor. Maneuverability considerations require low inlet distortion at high AOA/Beta conditions. Low distortion, in turn, requires separation-free inlet lip flow and shielding of the inlet at high AOA. Finally, good subsonic and supersonic cruise performance requires high inlet recovery, low drag, good stable range, and effective boundary layer management (BLM) with minimum drags. These requirements can be achieved individually within the current low observable (LO) inlet technology data base. However, the combination of all these requirements results in new design challenges for which no complete technology base exists. Design trade studies are necessary to quantify the sensitivities of these requirements to design selections, and to prioritize future aerodynamic and RCS research.

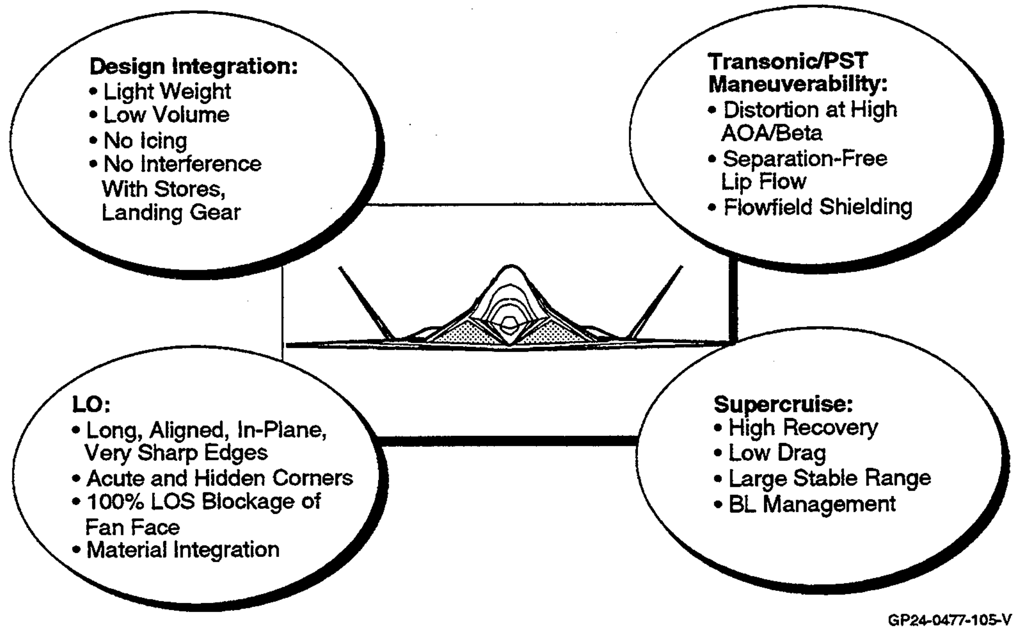

Figure 1. LO Inlet Design Drivers

The objective of this program was to provide a better understanding of these sensitivities and database deficiencies through a conceptual design and trade study for advanced fighter and attack aircraft concepts. The Multi-Role Fighter (MRF) is a future USAF initiative to replace the F-16 in both Battlefield Air Interdiction (BAI), and Defensive Counter-Air (DCA) roles. Notional aircraft propulsion systems for this role are characterized by single-engine installations and air induction systems designed for low detectability, supersonic flight, and superior maneuverability. The Advanced Medium Attack (AMA) bomber is a future USN/USAF initiative to replace the A-6, F-111, F-15E and F-117A in the Deep Interdiction (DI) role. Notional aircraft candidates for this role are characterized by twin-engine installations, and air induction systems designed for very low detectability and carrier suitability (superior static and low speed performance). Trade studies on all aspects of notional MRF and AMA aircraft air induction system design have been conducted to identify the most significant problems facing military aircraft designers over the next decade.

This program was conducted in a three task technical approach illustrated in Figure 2. In Task I – Concept Identification, notional MRF and AMA system requirements were postulated, and six notional fighter and attack aircraft were conceptually designed to meet these requirements. In Task II – Trade Studies, experts in air induction system design and development were interviewed to develop Quality Function Deployment (QFD) matrices for MRF and AMA weapon systems to assess the impact of air induction system design features on desired weapon system characteristics. The QFD matrices were then analyzed to determine the five most important trade study issues for further investigation. These five trade issues; the inlet external diffuser (i.e., inlet ramps, cowl and sidewall configuration) and integration, the inlet cowl lip geometry and integration, the subsonic diffuser configuration, the engine front frame configuration, and the inlet material selection/integration, were all examined using advanced design techniques and data bases. The QFD matrix and trade study results were then used to down select to “best” notional fighter and attack aircraft. In Task III – Research Programs, advanced design and technology data base deficiencies were identified to highlight the highest payoff areas for future research. Using this information, technology roadmaps were developed to insure availability of relevant, high quality data bases in time to aid future aircraft air induction system designers. Wind tunnel test plans were then assembled to address the aerodynamic development portions of the roadmap. Computational Fluid Dynamic (CFD) analyses were run at design point flight conditions for the two selected configurations to insure acceptability of the basic air

induction system aerodynamic characteristics. Conceptual wind tunnel model designs, with high payoff test parametrics, were then defined based on existing NASA hardware.

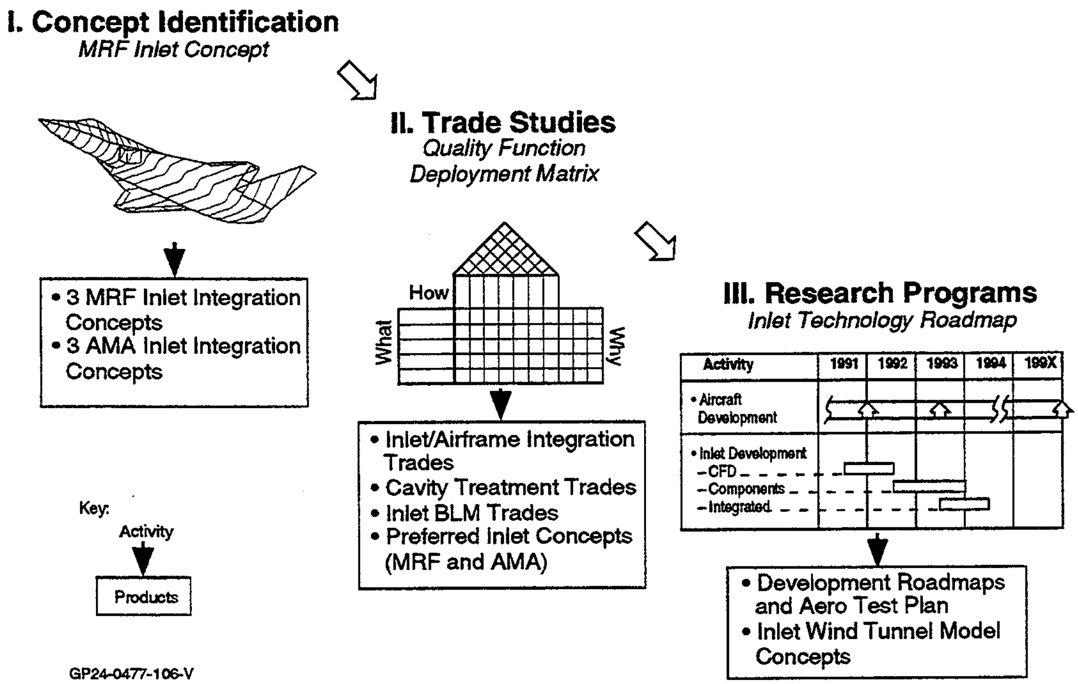

Figure 2. Study Technical Approach

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2.0 TASK I – CONCEPT IDENTIFICATION

In Task I, notional MRF and AMA aircraft requirements were defined, and three single engine MRF and three AMA twin engine propulsion system concepts were identified. Each concept included definition of the complete air induction system, including the airframe integration, aperture design, and subsonic diffuser characteristics. The Task I study flowchart is illustrated in Figure 3.

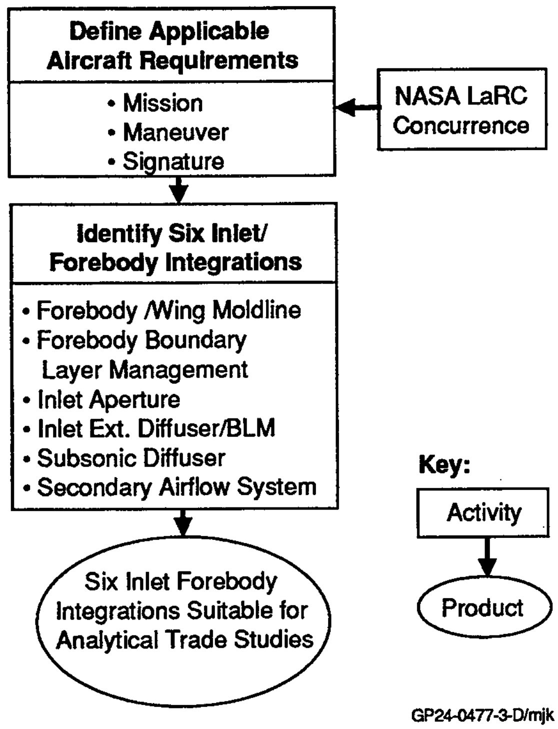


Figure 3. Task I – Concept Identification

2.1 SYSTEM REQUIREMENTS

To establish an appropriate design space for configuration identification, notional missions, maneuvers, and signature requirements were postulated for each weapon system requirement using operations analysis data from several sources, References 1, 2, 3, 4, 5. The Multi-Role Fighter (MRF) mission roles considered were the Battlefield Air Interdiction (BAI) air-to-ground mission, and the Defensive Counter Air (DCA) air-to-air mission. MRF design mission definitions and weapon load-outs are illustrated in Figure 4. MRF propulsion system sizing conditions which derive from these missions are a 4.7 G sustained turn requirement at Mach 0.9/30,000, and a Mach 0.8 to 1.6, 60-second dash requirement at 30,000 feet. The Advanced Medium Attack (AMA) mission role considered was the carrier-based Deep Interdiction (DI) mission. An AMA notional design mission definition and weapons load-out is illustrated in Figure 5. AMA propulsion system sizing conditions which derive from these missions are a 400 ft/min single engine Rate of Climb (SEROC) at Sea Level Static, Tropic Day conditions, and a 150 ft/sec specific excess power (Ps) requirement at Mach 0.75/Sea Level.

MRF transonic and supersonic maneuvering requirements are set by the air combat segments of Defensive Counter Air mission, and the maneuver capabilities of emerging threat fighters. These requirements can be met by transonic fighters such as the F-16, and F-18, Reference 6. However, a particularly worrisome new threat is a threat fighter which could combine thrust-vectoring nozzles with a helmet-mounted sight, and a thrust-vectoring air-to-air missile. This combination, which could be assembled with application of current propulsion and control technologies, may require U.S. fighters to incorporate Post-Stall

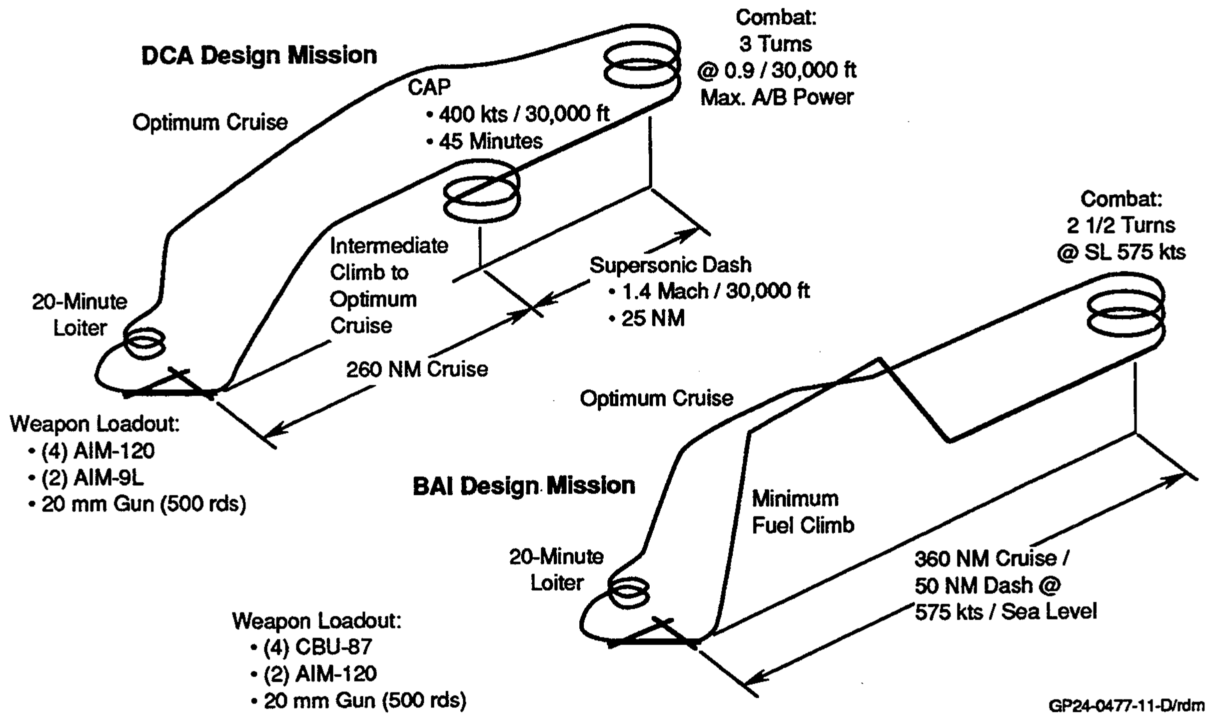


Figure 4. Notional MRF Mission Requirements

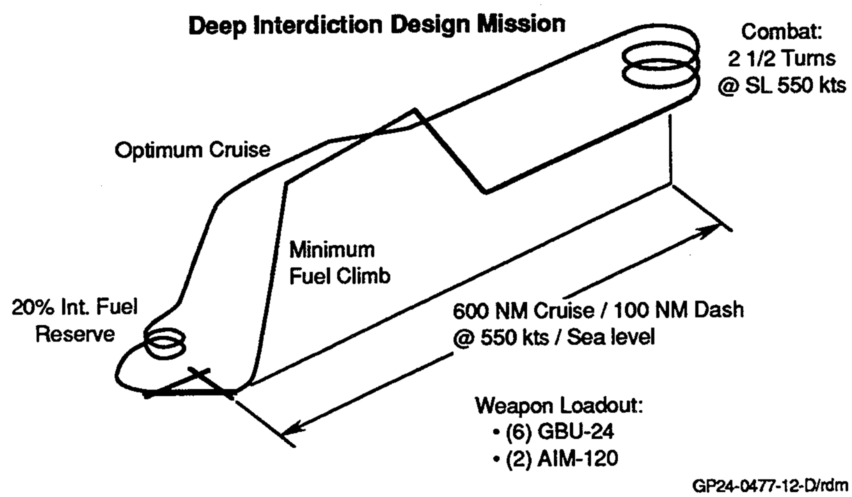


Figure 5. Notional AMA Mission Requirements

Technology (PST) to maintain air combat superiority at very low speeds. The addition of PST maneuvering considerably broadens the AOA and Beta envelopes at 0 to 200 knot airspeeds. The MRF will likely have to combine the transonic maneuver requirements of the F-16 with PST capabilities, resulting in the maneuver envelopes shown in Figure 6, derived from air combat flight simulation studies of effective PST maneuvers, Reference 7.

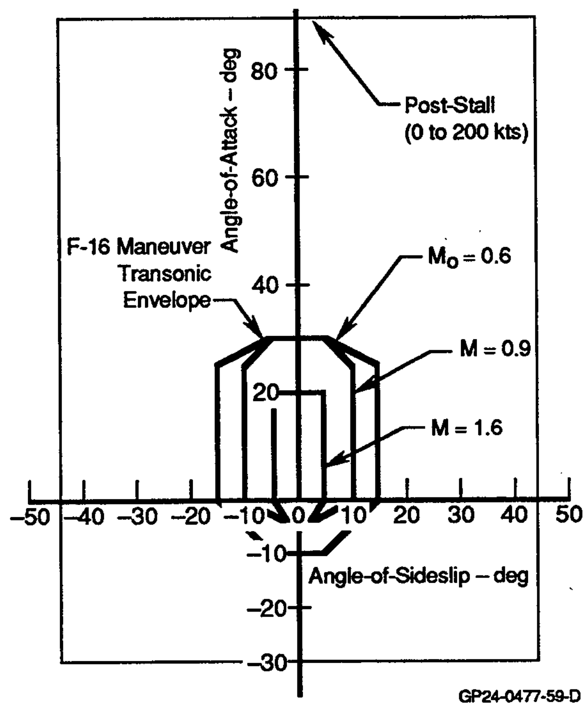


Figure 6. Notional MRF Maneuvering Envelope Requirements

AMA subsonic maneuver requirements are typical of tactical attack aircraft such as the USN A-6E and A12, References 2 and 7. The resulting AMA maneuver envelope is presented in Figure 7. These requirements while significantly less challenging than MRF requirements, demand high recovery and low inlet distortion at the AMA maneuver envelope limits, particularly in carrier takeoff land landing operations, because the AMA must operate at an aircraft thrust-to-weight less than one-half that of the MRF.

MRF and AMA signature requirements are defined by the need to successfully fly past or engage threat surface and airborne systems. Aircraft detection can be achieved using radar, infrared (IR), visual/electro-optical, or acoustic sensors. The most highly developed and longest range-detectors of aircraft signatures are radar systems. Most threat systems rely on a "net" of interconnected radars to detect, track, and fire on aircraft using surface-to-air missiles. Avoiding detection against the radar net thus requires substantially reduced radar signatures across a broad spectrum, Figure 8. The selection of signature goals for a weapon system is a difficult procedure which must balance the advantages of complete non-detectability against the cost of the required low observable technology. In addition, the availability of complementary survivability enhancements such as electronic countermeasures (ECM) and tactics such as terrain following/terrain avoidance influence the decision on the signature design philosophy (i.e., RCS vs. azimuth and elevation). Operational Analysis procedures such as the SURVIAC ESAMS missile engagement modeling, the USAF TAC BRAWLER and the MDC STRIKER mission analysis codes have been exercised for a number of conceptual fighter and attack aircraft concepts. The results of these studies for any given weapon system are sensitive, and often highly classified.

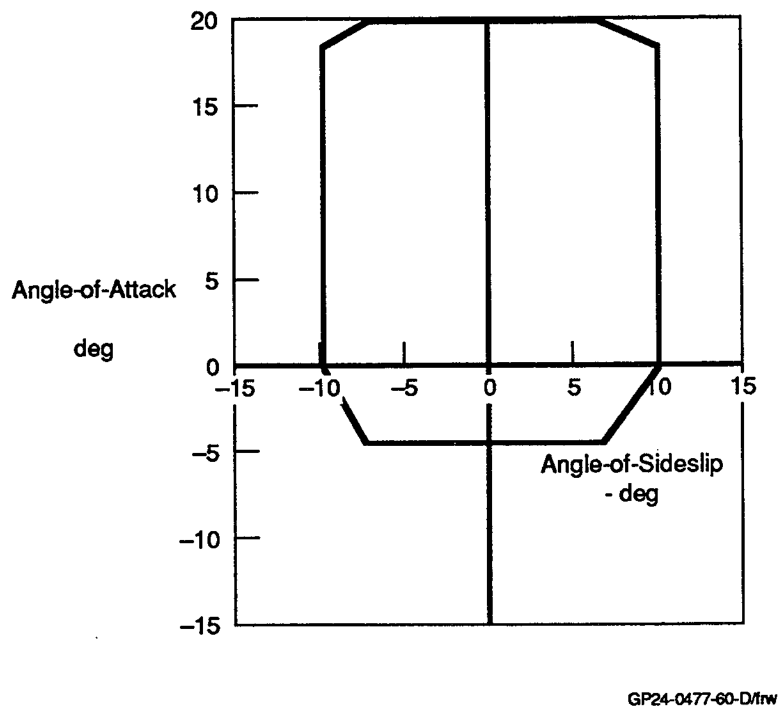


Figure 7. AMA Maneuvering Envelope Requirements

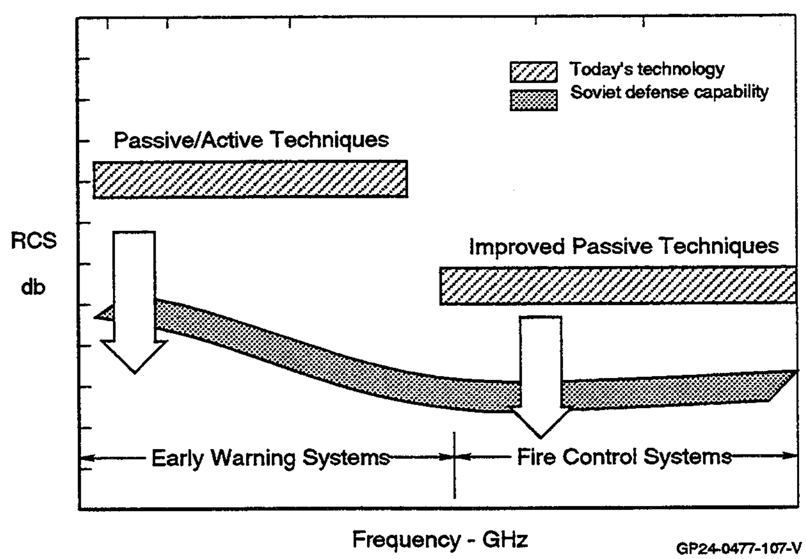


Figure 8. RF Signature Suppression Requirements

RCS design objectives for the notional MRF configurations are keyed to reduced RCS in the A/C frontal sector as shown in Figure 9. The "quiet zone" azimuth/elevation sectors, and radar frequencies band selected are a function of the anticipated threat "lay-downs" anticipated for the MRF Battlefield Air Interdiction mission. The RCS design objectives for the notional AMA aircraft are given in Figure 10. The "quiet zone" azimuth/elevation sectors and radar frequency bands selected are also a function of the anticipated threat "lay-down" for the AMA Deep Interdiction mission, and the anticipated use of terrain-following to minimize the radar horizon.

Objectives:

- Defeat Shooters
- Delay Detection by Early Warning Radars

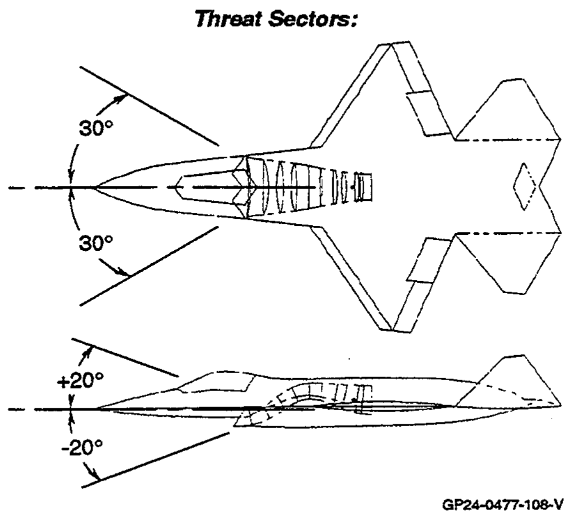


Figure 9. Notional MRF Signature Goals

Objectives:

- Defeat Shooters
- Eliminate Detection by Early Warning Radars
- Eliminate Detection by IRST's

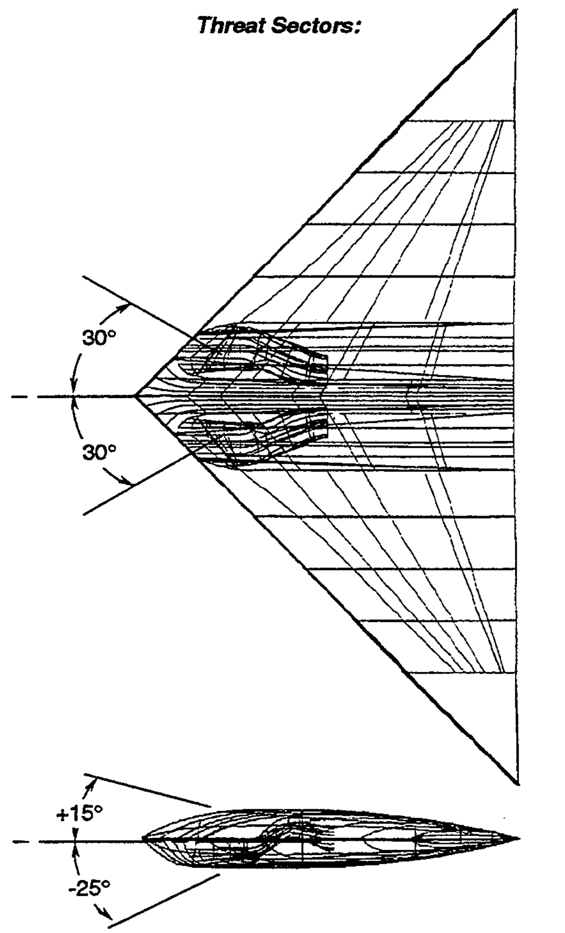


Figure 10. Notional AMA Signature Goals

Infrared (IR) signatures are also a concern for tactical aircraft, Figure 11. The inlet may be utilized to provide cooling air to the nozzle for tail sector hot part cooling for low altitude attack aircraft. This cooling air impacts the inlet sizing, boundary layer management, and internal ducting configuration.

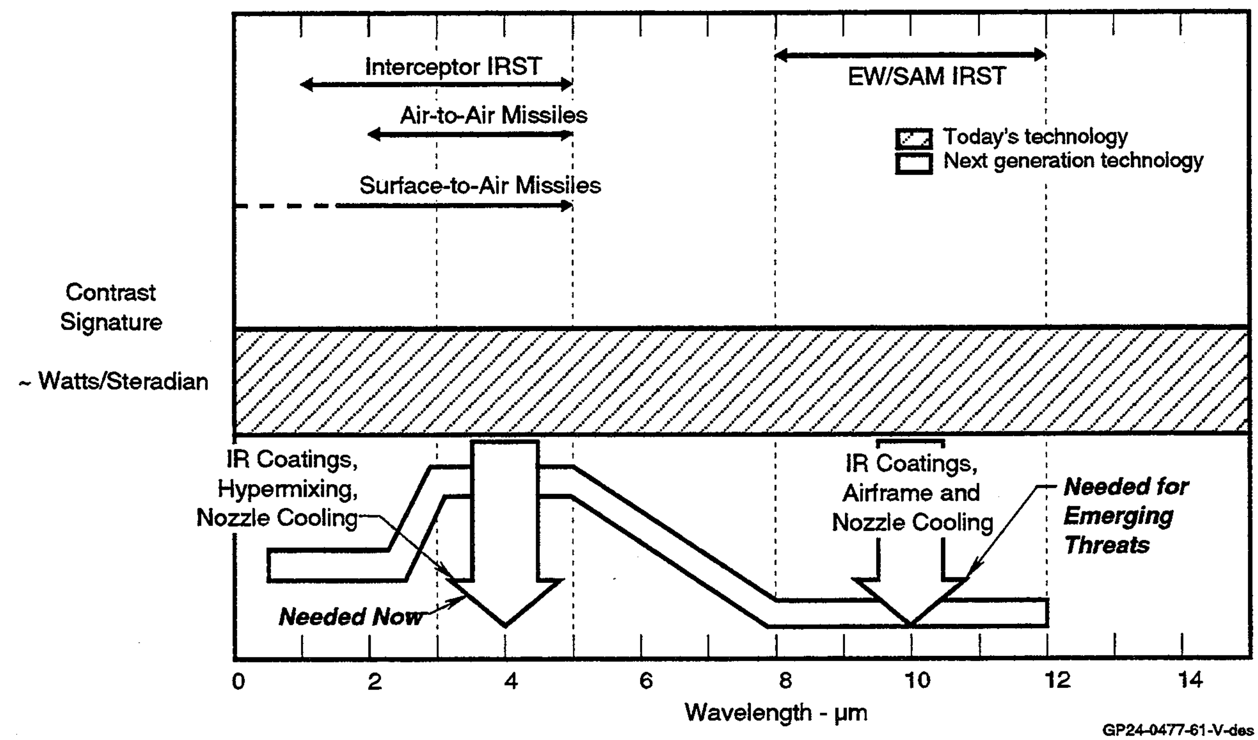


Figure 11. IR Signature Reduction Requirements

2.2 MULTI-ROLE FIGHTER (MRF) CONCEPT DEVELOPMENT

To meet the notional mission, maneuver and signature requirements assembled for the MRF, three single-engine, lightweight fighter concepts were selected from MCAIR's advanced design studies. These aircraft concepts are illustrated in Figure 12. All three aircraft are in the 30,000 to 40,000 lbm Takeoff Gross Weight (TOGW) class to meet the MRF mission requirements. A single Pratt and Whitney (PW) SE564 advanced turbofan engine was selected for the common power plant, giving an aircraft thrust/weight of approximately 1.0 and the capability to meet the sustained turn, and supersonic acceleration requirement, described in Section 2.1.

Each aircraft incorporates a unique inlet system consisting of a forebody, external compression ramps, splitter plate, forebody boundary layer diverter, inlet bleed system and subsonic diffuser. All the forebodies utilize diamond or chined cross-sections to reduce nose and beam specular reflections. All inlet diverter, ramp and cowl edges are swept or serrated to align with planform angles which are parallel to the wing and empennage leading edges. This allows the returns from these components to align with the main planform returns. All three subsonic diffusers utilize offset to hide the engine face at nose-on azimuth. The MRF 1006 and 2001 rely on advanced front frames to hide the fan rotor at some azimuths and elevations. The MRF 1209 subsonic diffuser is designed to provide 100% line-of-sight obscuration of the engine face at all viewing angles. The MRF boundary layer diverters have been designed using design criteria developed under Reference 9, to minimize RCS scattering including use of flush diverters at minimum height. All MRF inlet design features have been selected to support Task I trade studies both between configurations and about a given configuration.

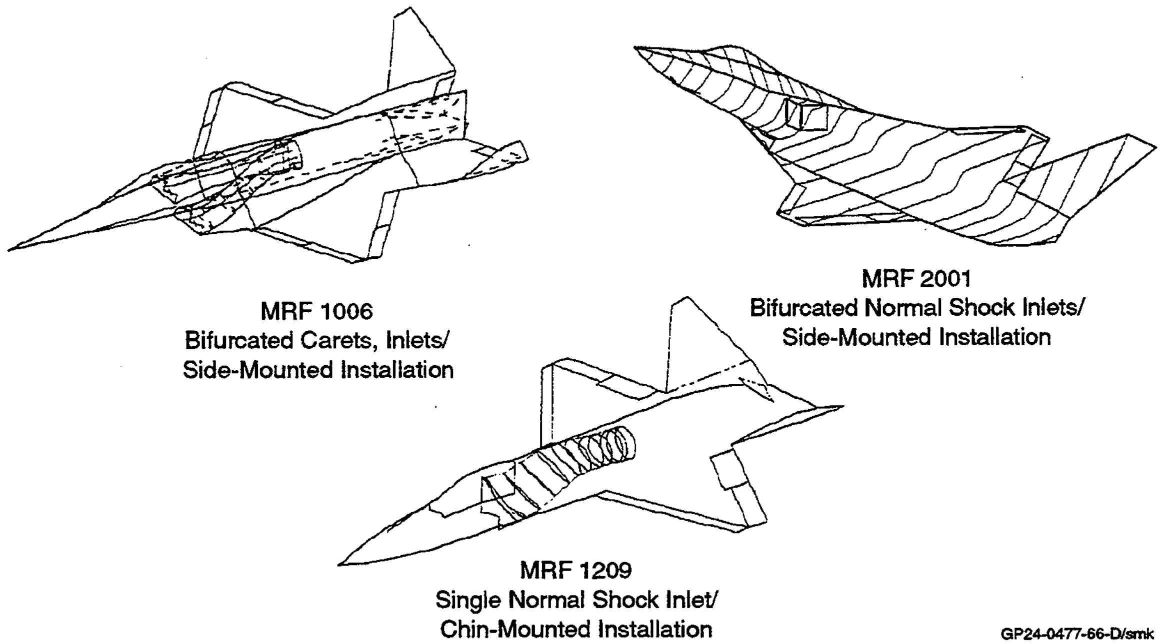


Figure 12. Multi-Role Fighter Configurations

The MRF 1006 configuration was developed for the Reference 10 study, and refined for this study through redesign and sizing of the air induction system. The MRF 1006 incorporates a bifurcated air induction system, Figure 13, consisting of a diamond cross-section LO forebody, twin side-mounted 7° compression symmetrical "caret" inlets, an eight-edge planform-aligned serrated cowl, and a bifurcated subsonic

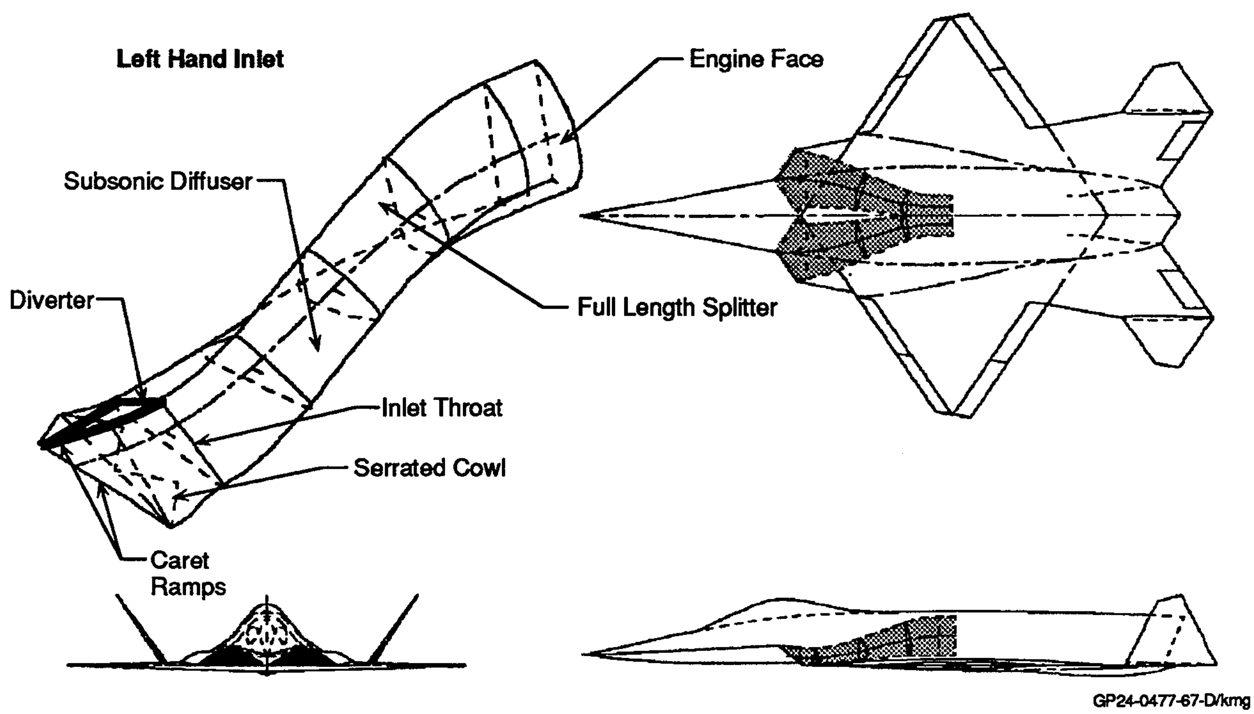


Figure 13. MRF 1006 Inlet/Air Induction System Design

diffuser, utilizing a full-length splitter from the engine face forward. The design includes two short, (2.25"), flush external boundary layer diverters between the forebody and inboard caret ramps, and simple LO bleed plates on the caret compression surfaces.

The inlet was sized for the PW SE564 turbofan engine at Mach 1.6, 36089', Figure 14, using MCAIR's inlet sizing program, "INSAD". (INSAD's sizing procedures are described in detail in Appendix "A"). The resultant inlet capture area is 1152 in^2, with a 953 in^2 throat, (21% contraction – 15% external/6% internal). Because the inlet is fixed, the inlet is oversized at all other flight conditions, by as much as 12% at Mach 1.0, and by 4% at Mach 1.8. By comparison, the F/A-18 C/D total inlet capture area is 1221 in^2 with 36% contraction, (15% external/18% internal). The large difference in internal contraction is due to the relative sharpness of the MRF 1006 cowl lip, which has been designed for low observables and low supersonic drag.

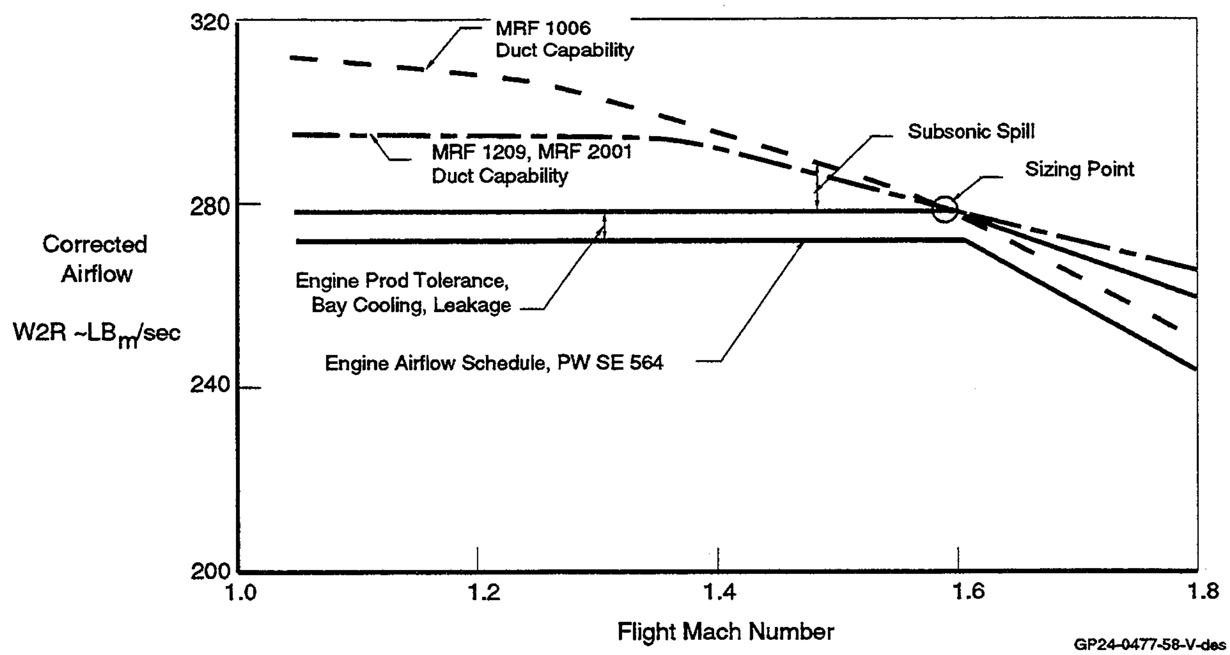


Figure 14. MRF Inlet Capture Area Sizing

The MRF 1006 bifurcated diffuser, Figure 15, has a length-to-engine face diameter ratio (L/D) of 3.8, a vertical offset ($\Delta y/D$), of 0.5, and a horizontal offset ($\Delta z/D$), of .64 for a combined offset of .81. Offset as a function of length (D/L), is .21. This offset is well within the "safe" zone in terms of diffuser turning-induced stall, Reference 11. The diffuser area distribution, has been designed to rapidly reduce transport Mach No. to increase recovery, Figure 16. The resultant diffuser area ratio is approximately 1.38.

The MRF 1209 configuration was developed for this study. This aircraft incorporates a single air induction system, Figure 17, consisting of a flat-bottom chined cross-section forebody, a single chin-mounted normal shock inlet, a four-edge planform-aligned serrated cowl, and a single serpentine subsonic diffuser. The design incorporates a single short flush 2.1" tall, internal boundary layer diverter which separates the fuselage from the inlet splitter plate. The diverter flow is ducted internally and exhausted through louvered exits on the fuselage topside. The splitter plate includes a compartmented LO porous bleed system. The inlet was sized for a PW SE564 turbofan at Mach 1.6, 36089', Figure 14, using the INSAD program. The resultant inlet capture area is 936 in^2 with an 888 in^2 throat, (5% contraction – all internal).

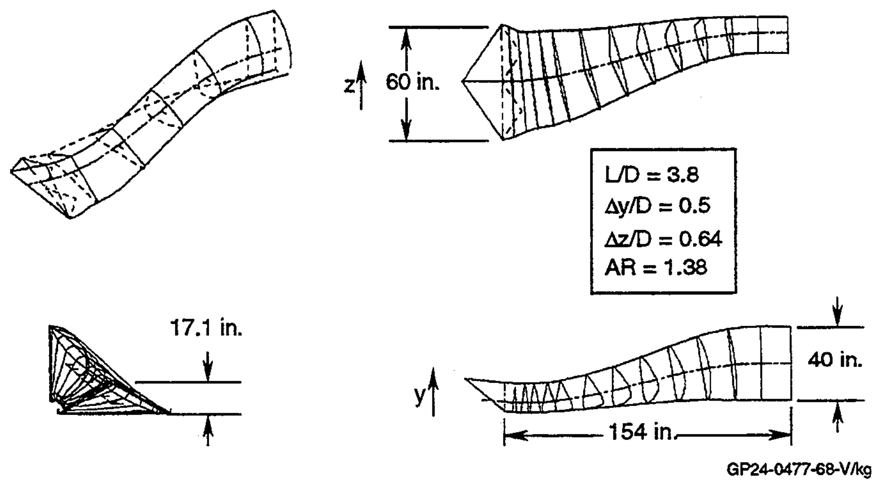


Figure 15. MRF 1006 Subsonic Diffuser Geometry

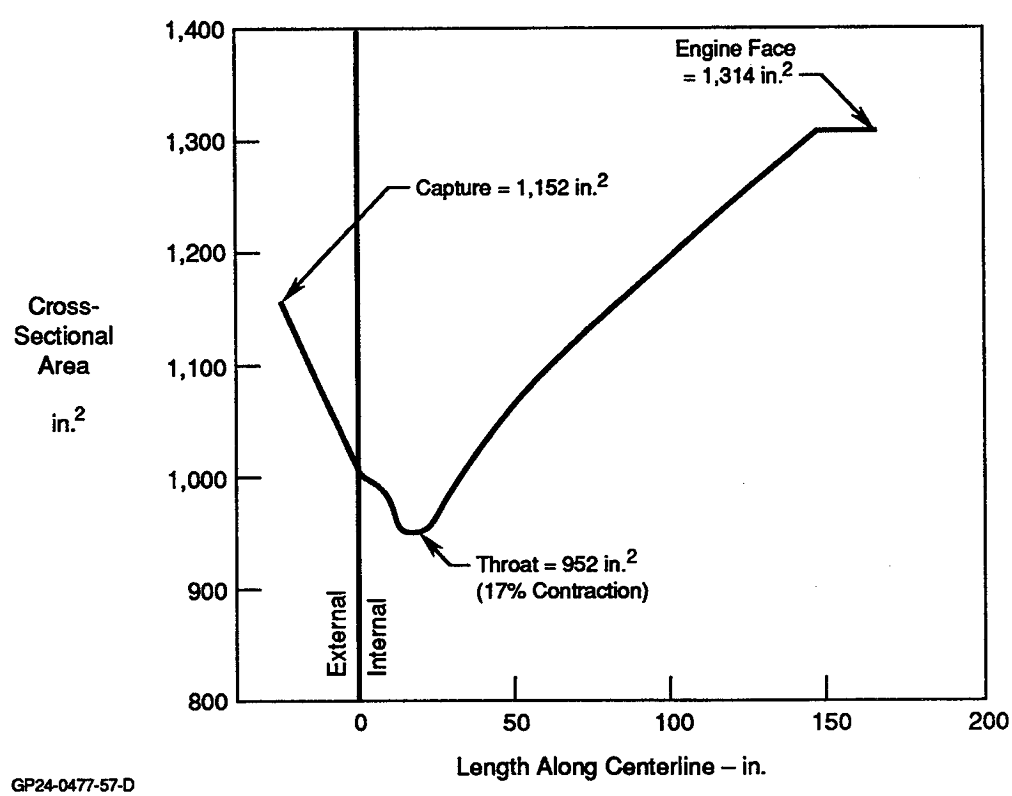


Figure 16. MRF 1006 Subsonic Diffuser Area Distribution

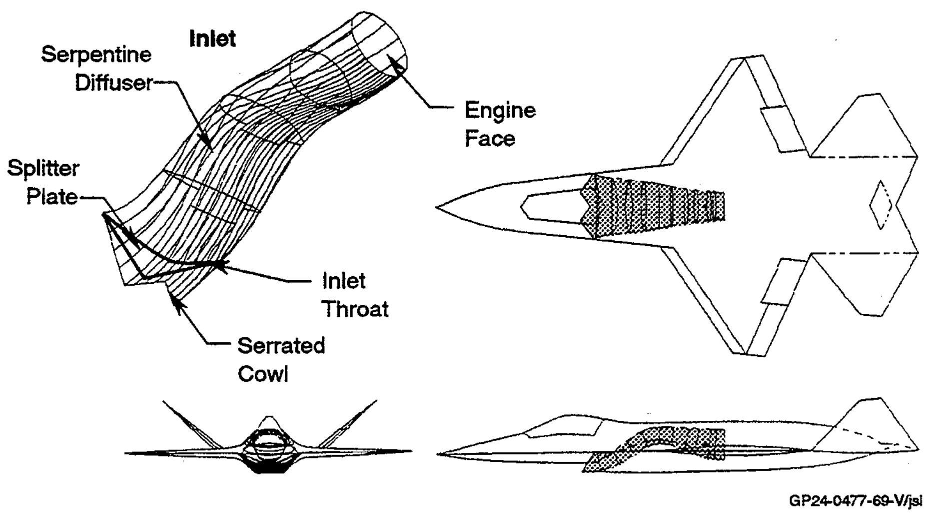


Figure 17. MRF 1209 Inlet/Air Induction System Design

The MRF 1209 serpentine diffuser, Figure 18, has an L/D of 4.4, a $\Delta y/D$ of .97 for the first half and .26 for the second half with no lateral offset. This duct provides 100% obscuration of the compressor face at all viewing angles. Offset as a function of length is .49 and .11 for the first and second halves, respectively. These offsets are on the borderline of first stall, but well within manageable limits using passive, (area control, Gerlach shaping, vortex generators), or active (bleed/blowing) boundary layer management, Reference 11. The diffuser area distribution, Figure 19, has been designed to control boundary layer pressure gradients through the use of a 5% contraction in the region of greatest turning. The diffuser area ratio is approximately 1.48.

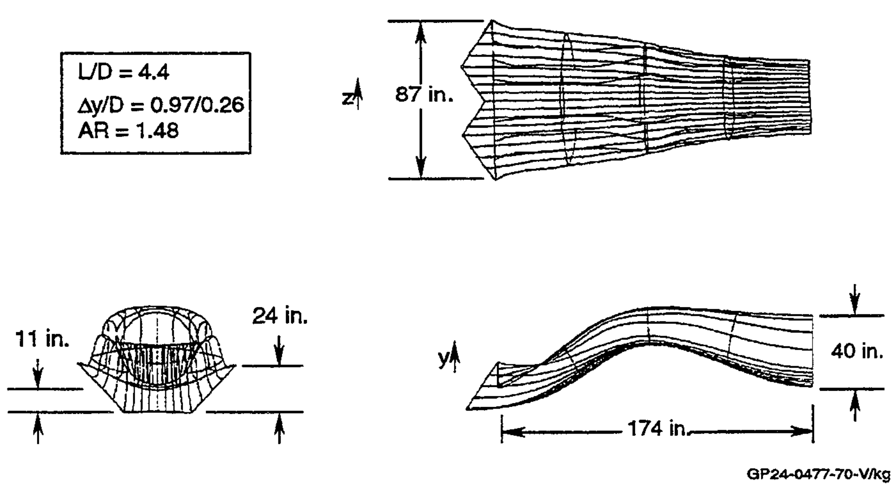


Figure 18. MRF 1209 Subsonic Diffuser Geometry

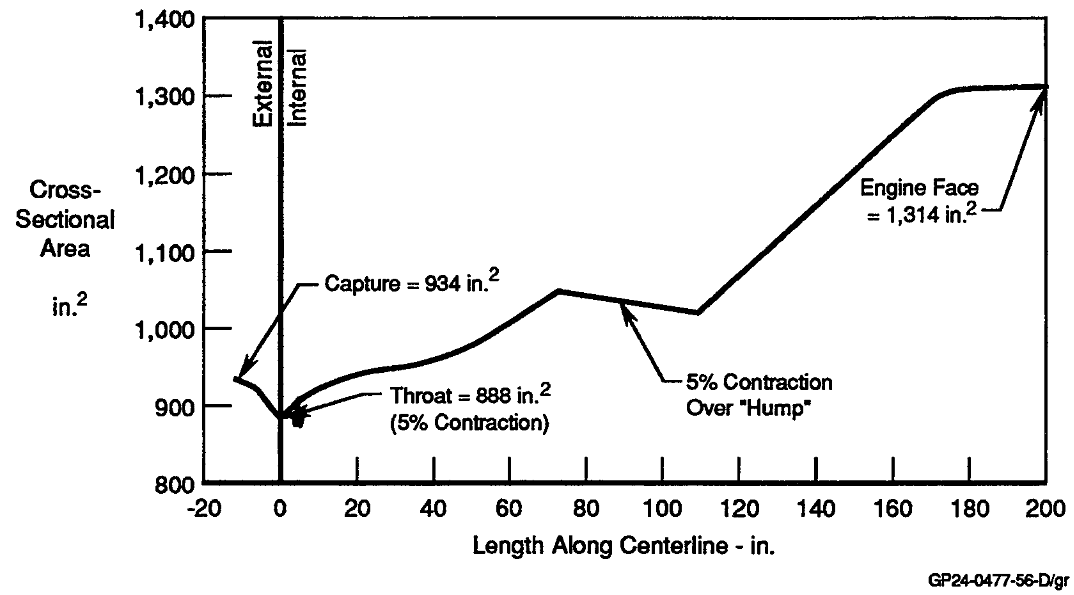


Figure 19. MRF 1209 Subsonic Diffuser Area Distribution

The MRF 2001 configuration was developed in MCAIR's advanced design IRAD program and refined for this study. Like the MRF 1006, this aircraft incorporates a bifurcated air induction system, Figure 20, consisting of a chined forebody, a set of overhead leading edge extensions, twin side-mounted 2° hybrid asymmetric caret/normal shock compression inlets, two two-edge swept cowl lips, and a very short bifurcated diffuser which includes a full-length splitter. The design includes two short, (2.5"), external pitot boundary layer diverters between the forebody and the inboard inlet ramps, and compartmented LO bleed plates distributed on the inlet ramps, cowl lip, and the forebody leading edge extensions.

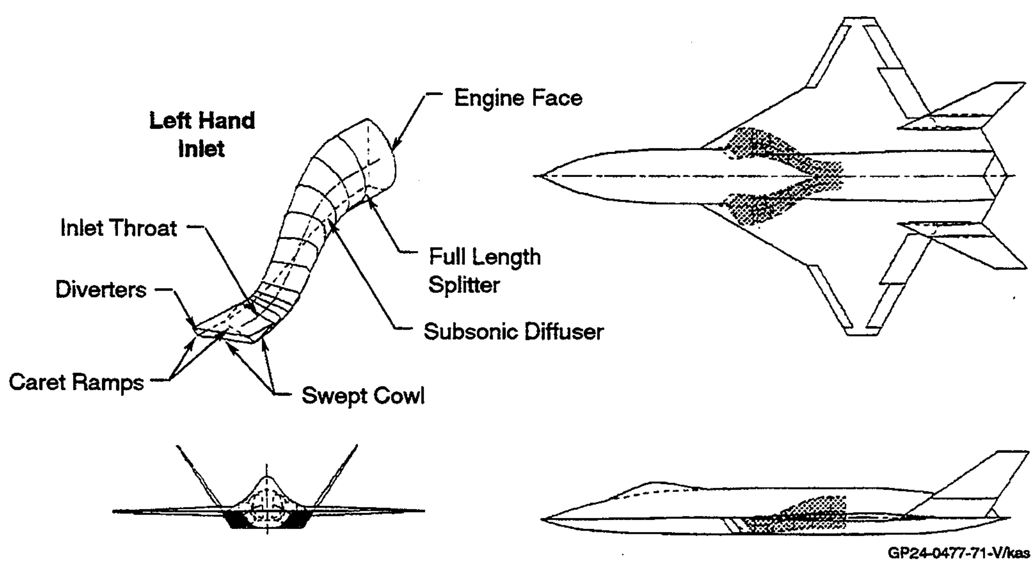


Figure 20. MRF 2001 Inlet/Air Induction System Design

This inlet was also sized for a PW SE564 turbofan at Mach 1.6, 36089', Figure 14. The inlet capture area is 1000 in^2 with a 872 in^2 throat, with 13% contraction, (8% external/6% internal). The external contraction provides some precompression upstream of the normal shock improving bleed system performance.

The MRF 2001 bifurcated diffuser has a L/D of 2.9, a $\Delta y/D$ of .44, and a $\Delta z/D$ of .88 for a combined offset of .99. Offset as a function of length Δ/L is .335 and is highly three-dimensional, as shown in Figure 21. This offset is outside of the "safe" zone defined in Reference 11. This offset makes the MRF 2001 diffuser aerodynamics higher risk than the other concepts. The MRF 2001 diffuser area distribution is presented in Figure 22.

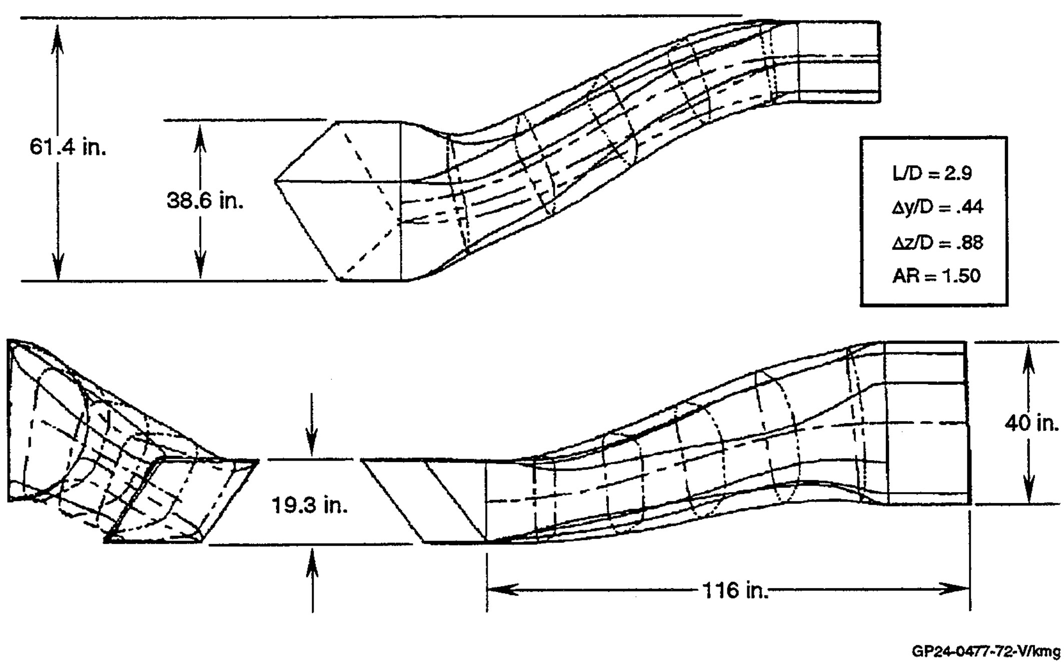


Figure 21. MRF 2001 Subsonic Diffuser Geometry

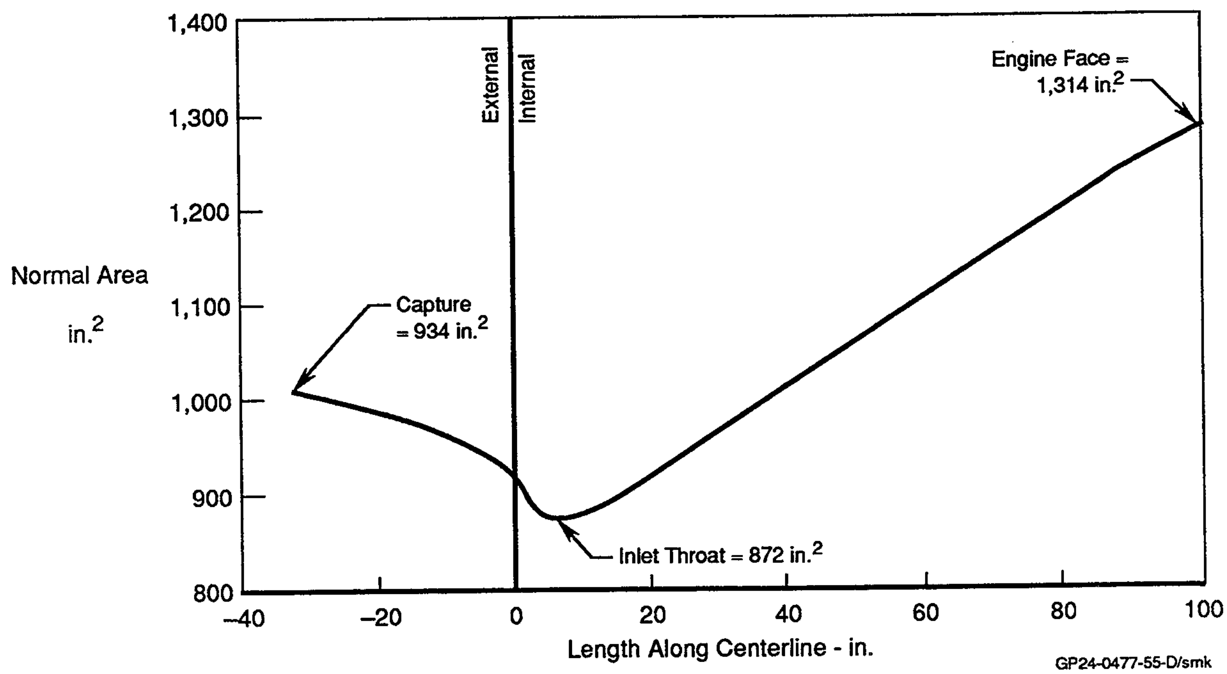


Figure 22. MRF 2001 Subsonic Diffuser Area Distribution

2.3 ADVANCED MEDIUM ATTACK (AMA) CONCEPT DEVELOPMENT

To meet the mission, maneuver and signature requirements assembled for the AMA, three twin-engine low observable attack aircraft were selected from MCAIR's advanced design IRAD studies, or developed expressly for this program. These aircraft concepts are illustrated in Figure 23. All three aircraft are in the 65,000 to 70,000 lbm TOGW class, to meet the AMA mission requirements. Two non-afterburning GE F412

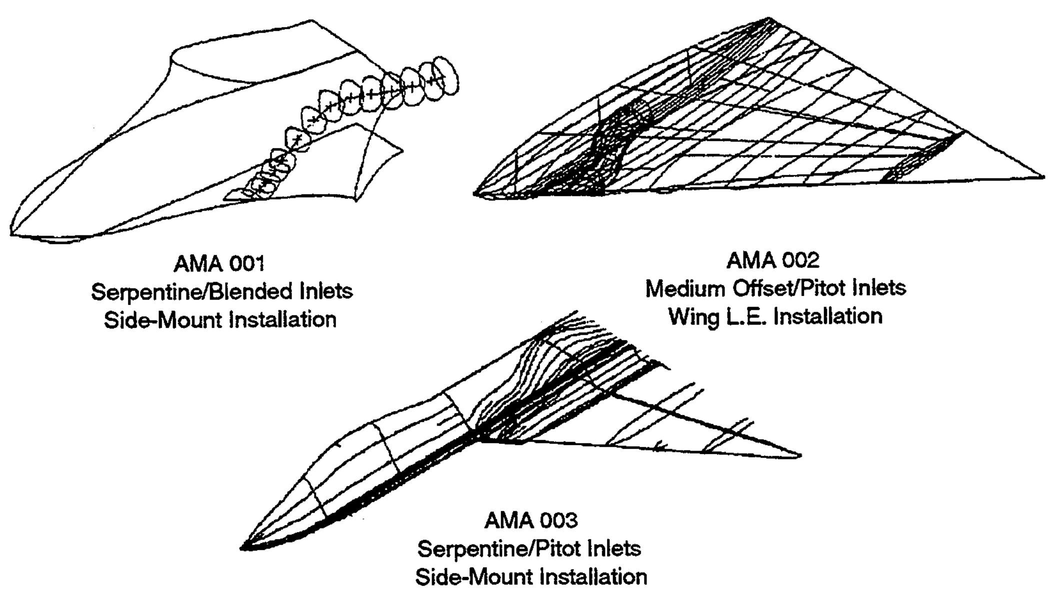


Figure 23. Advanced Medium Attack Configurations

turbofan engines were selected as common powerplants for all concepts, giving a SLS Tropic Day thrust/weight ratio of approximately 0.4, and the capability to meet the Single Engine Rate of Climb (SEROC) and attack ingress specific excess power (Ps) requirements described in Section 2.1.

Each aircraft forebody, inlet integration, and air induction system is unique. The forebodies and inlet apertures have been designed to meet RCS goals through the use of shaping and material integration. The AMA 001 and AMA 003 concepts utilize chined or diamond cross-section forebodies to reduce nose and beam specular reflections. The AMA 002, a flying wing concept, dispenses with a forebody altogether. All concept inlet edges are maximum length, and swept at planform angles which are parallel to the wing and empennage leading edges. All forebody boundary layer management concepts have been designed for minimum signature contributions. All three subsonic diffusers utilize offset to hide the engine face nose-on. The AMA 001 and AMA 003 subsonic diffusers are designed to provide 100% line-of-sight obscuration of the engine face at all viewing angles. The AMA 002 relies on an advanced front frame to hide the fan rotor at off nose azimuths and elevations. Similar to the MRF inlets, all AMA inlet design features have been selected to support Task II trade studies both between configurations, and about a given configuration.

The AMA 001, Figure 24, was developed in MCAIR's advanced design IRAD studies, and modified for inclusion in this study through refinement and sizing of the air induction system. The AMA 001 incorporates twin left and right pitot inlets which are "blended" into a chined forebody, a porous bleed forebody boundary layer management system sized to feed 15% of the captured airflow to the exhaust nozzle for nozzle hot part cooling, and a relatively long serpentine subsonic diffuser which provides 100% engine face obscuration.

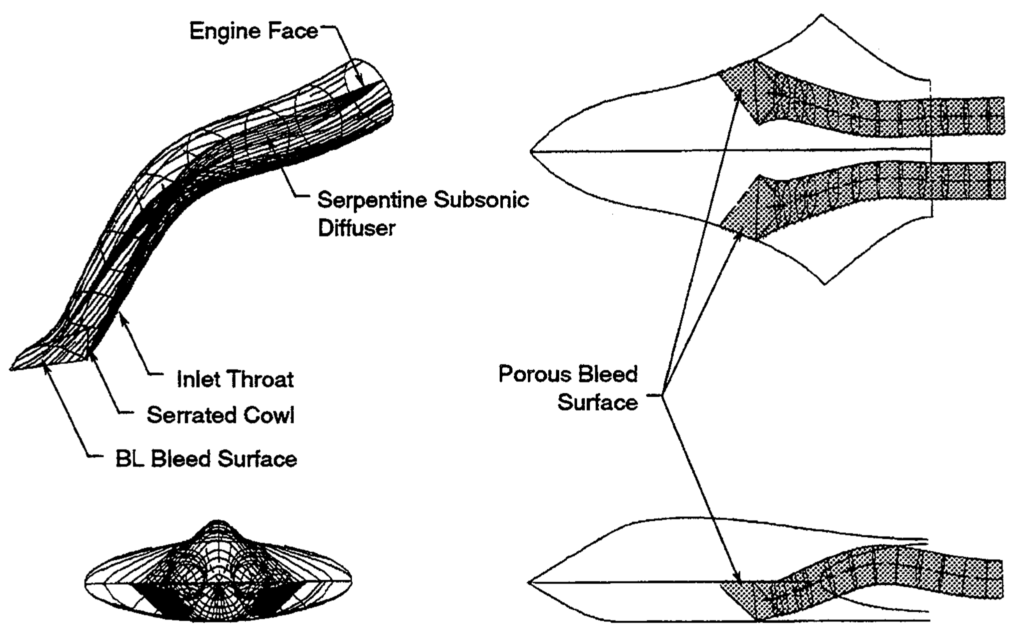


Figure 24. AMA 001 Inlet/Air Induction System Design

The inlet throat was sized for the F412-GE-400 turbofan engine at Mach 1.0, 36089', which has a rated airflow of 209 lbm/sec. The resultant inlet capture area is 740 in^2 per side with a 645 in^2 throat area, (13% contraction – all internal). By comparison, the F/A-18 inlet throat area is approximately 450 in^2 per side with 18% internal contraction. The AMA inlet throat was sized to pass 209 lbm/sec of airflow at 95% critical flow per unit area, or a throat Mach No. of .767.

The AMA 001 serpentine diffuser, Figure 25, has a L/D of 6.1, a total offset (Δ/D) of 1.174 for the front half, and a Δ/D of 0.40 for the back half with displacement in both vertical and horizontal planes. Offset as a function of length, Δ/L, is .326 for the front half and .125 for the back half. These offsets are on the borderline of first stall per Reference 11, but well within manageable limits using passive boundary layer management. The diffuser area distribution, Figure 26, has been designed to provide rapid diffusion just after the throat to minimize frictional losses, and a smoothly increasing area to the engine face station. The diffuser area ratio is approximately 1.26.

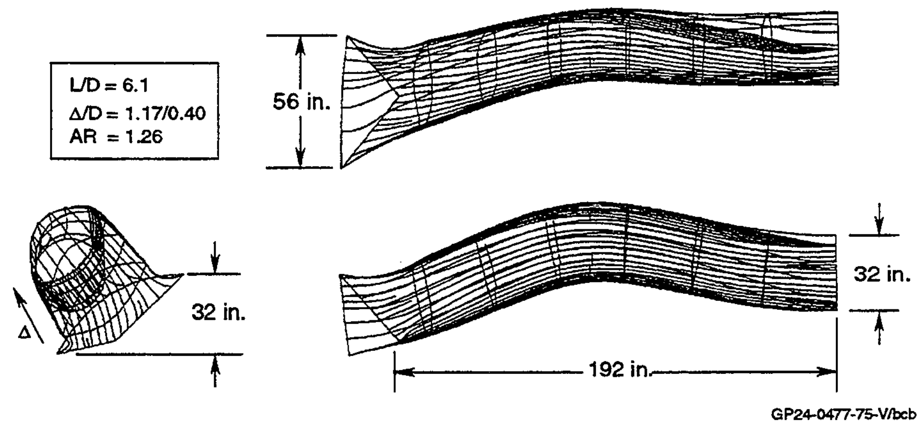


Figure 25. AMA 001 Subsonic Diffuser Geometry

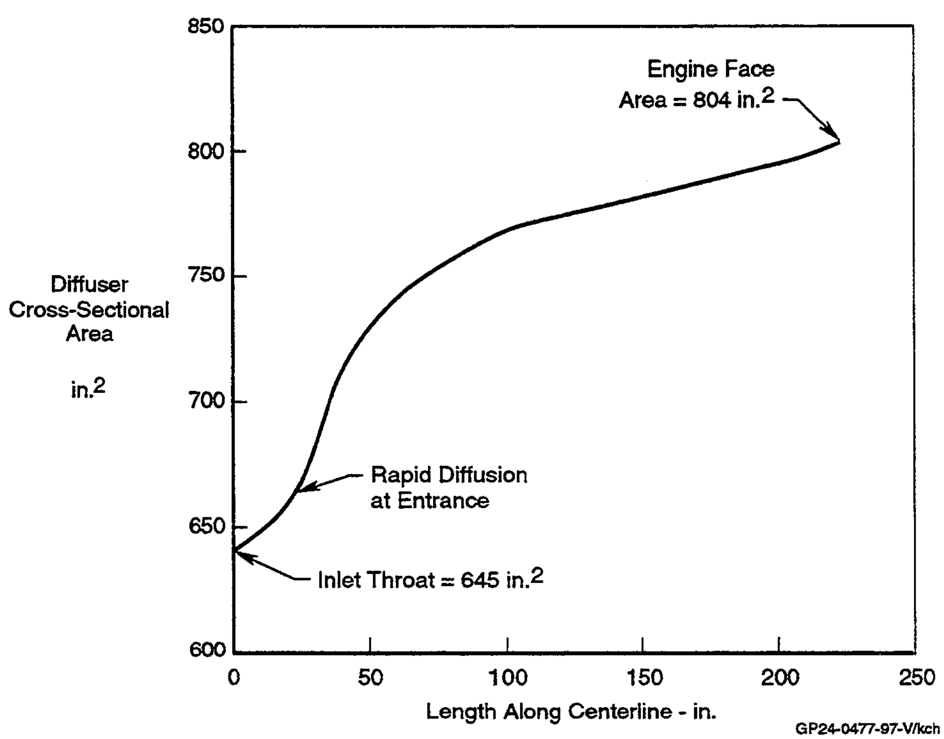


Figure 26. AMA 001 Subsonic Diffuser Area Distribution

The AMA 002, Figure 27, was developed for this study as a generic flying wing concept, loosely patterned after the A-12 configuration. The AMA 002 incorporates twin left and right pitot inlets which are blended into the wing leading edge, a short serpentine diffuser with partial engine face obscuration, and a top-mounted ram air scoop on the aircraft aft fuselage to provide hot part cooling air to the exhaust nozzles. Because of the inlet's leading edge location, no forebody BLM is required or incorporated. The inlet incorporates 910 in^2 capture area with 30% internal contraction to allow full blending into the wing contours. The secondary ram air scoop is sized at 240 in^2 to capture 15% of the rated engine airflow.

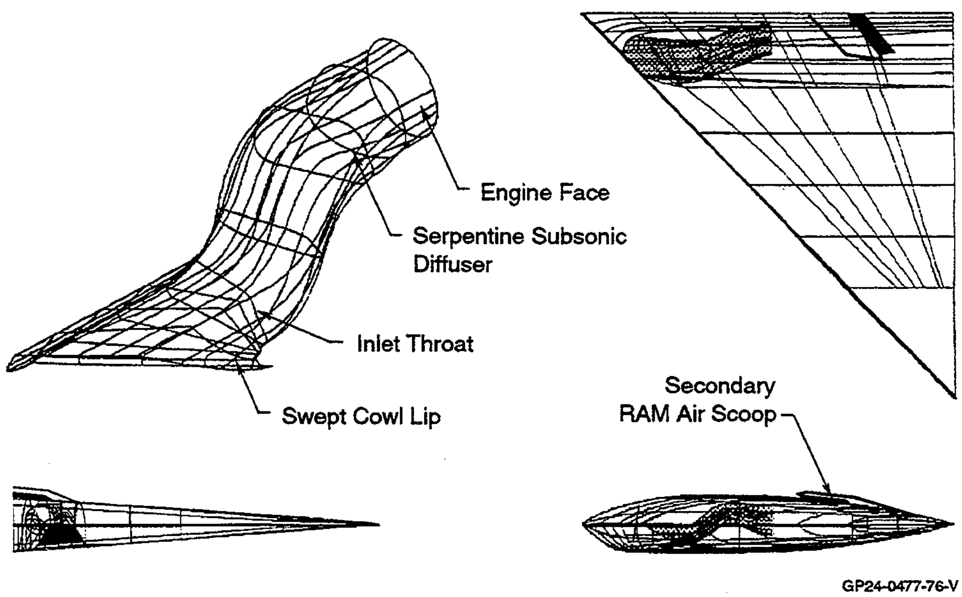


Figure 27. AMA 002 Inlet/Air Induction System Design

The AMA 002 serpentine diffuser, Figure 28, has an L/D of 3.0, a total offset, (Δ/D), of .855 for the front half, and a total offset of .58 for the back half with displacement in both the vertical and horizontal planes. Offset as a function of length, Δ/L, is .503 for the front half and .411 for the back half. These offsets are in the high risk category, and may require active BLM (bleed or blowing) to maintain unseparated flow to the engine face. The diffuser area distribution, Figure 29, has been designed to provide rapid diffusion just after the throat, and a smoothly increasing area through the turns to the engine face. The total diffuser area ratio is 1.26.

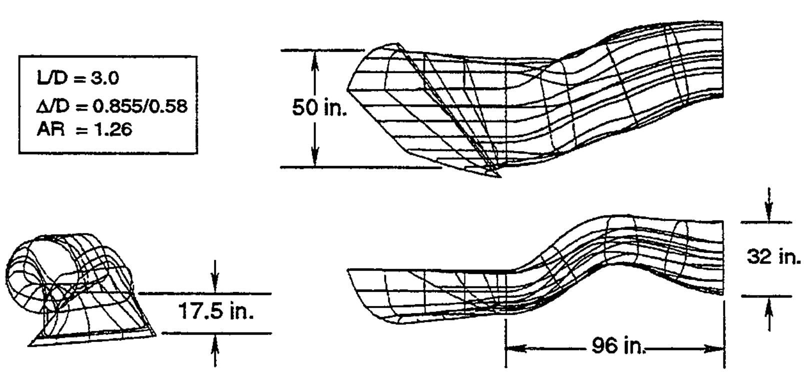


Figure 28. AMA 002 Subsonic Diffuser Geometry

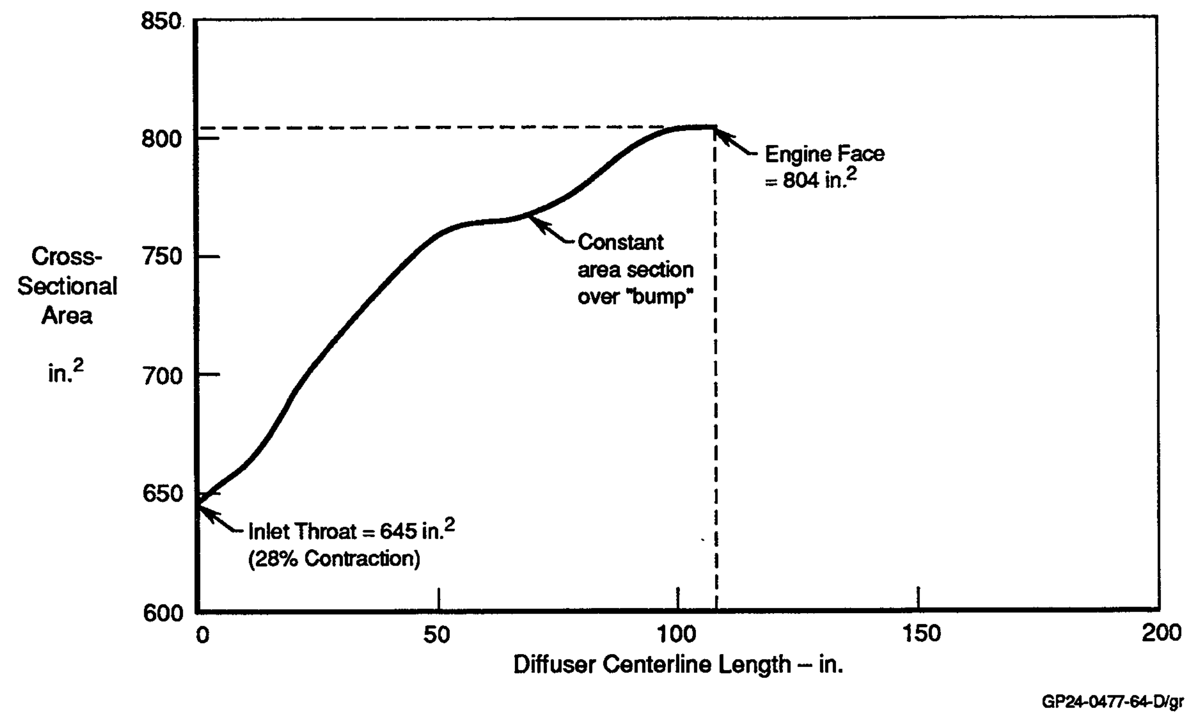


Figure 29. AMA 002 Subsonic Diffuser Area Distribution

The AMA 003, Figure 30, was developed for this study as a generic conventional forebody-wing concept. The AMA 003 incorporates a long diamond-shaped forebody with twin left and right subsonic parallelogram inlets which are blended into the wing/forebody "armpit", two short, (1.75"), external diverters between the forebody and the inlet inboard sidewall, and a medium-length serpentine diffuser, which provides 100% engine face obscuration. The inlet was oversized by 15% to provide all nozzle secondary airflow to a 1" annulus at the engine face station which vents to a pressurized engine bay, and then to the ejector nozzle secondary plenum. The inlet capture area is 820 in^2 with a 10% internal contraction ratio.

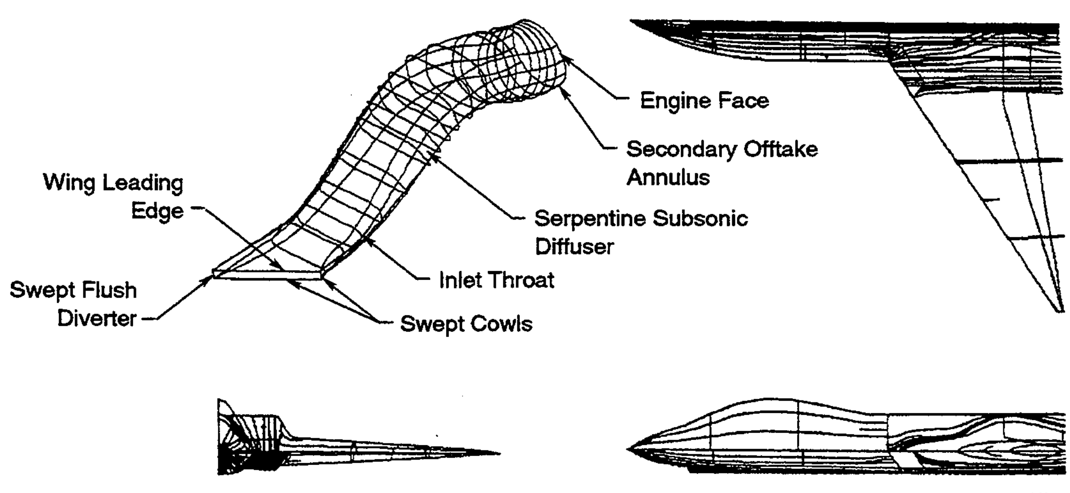


Figure 30. AMA 003 Inlet/Air Induction System Design

The AMA 003 serpentine diffuser, Figure 31, has an L/D of 4.5, a vertical offset, ($\Delta y/D$), of 1.08 for the front half and $\Delta y/D$ of .50 for the back half. Horizontal offset for this diffuser is negligible. Offset as a function of length, Δ/L, is .412 for the front half, and .263 for the back half. These offsets are borderline in terms of aerodynamic risk and probably require some form of BLM to insure freedom from separation. The diffuser area distribution, Figure 32, has been tailored to minimize separation potential. The total diffuser area ratio is 1.26, including the secondary airflow annulus, which represents 15% of the diffuser exit area.

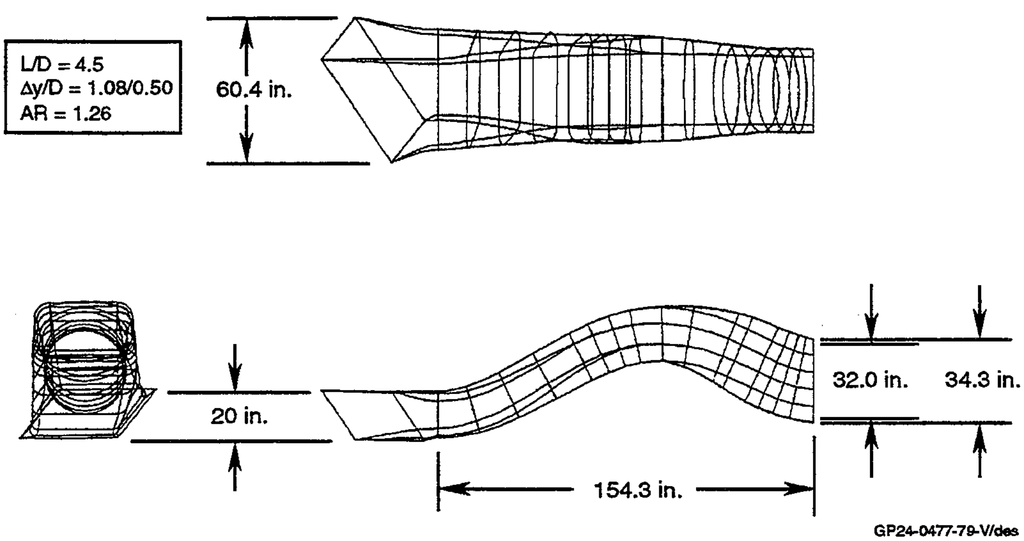


Figure 31. AMA 003 Subsonic Diffuser Geometry

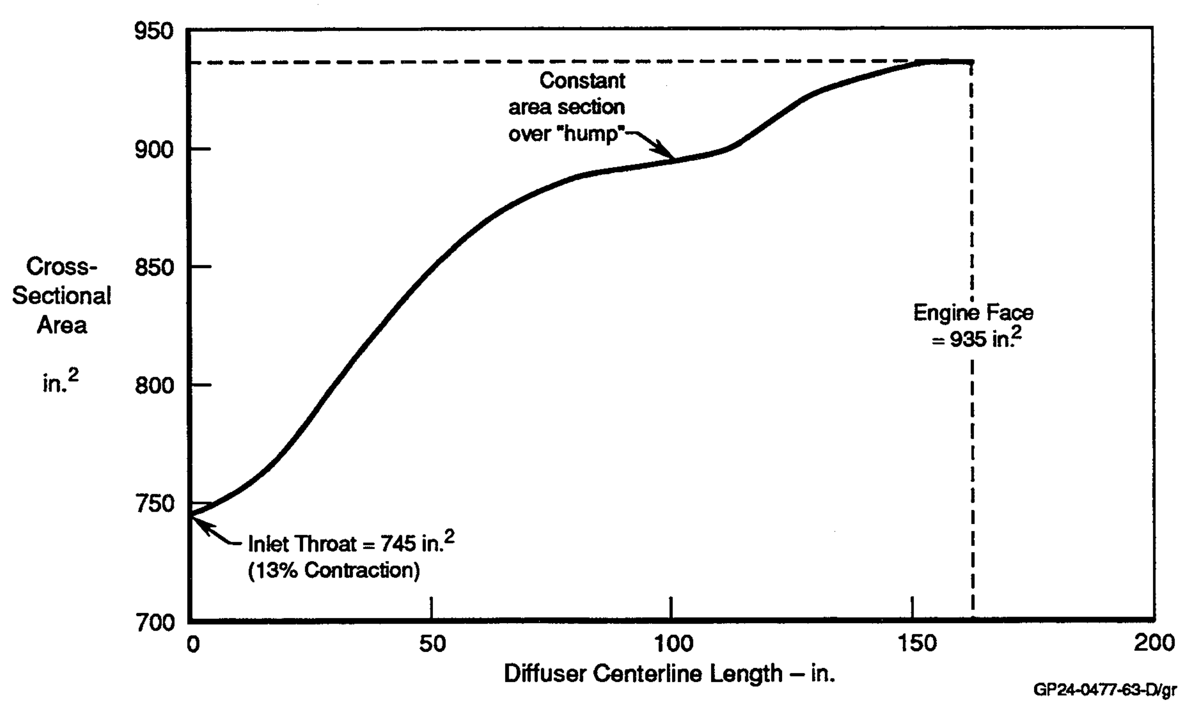


Figure 32. AMA 003 Subsonic Diffuser Area Distribution

3.0 TASK II – TRADE STUDIES

In Task II, we developed a Quality Function Development (QFD) matrix for notional MRF and AMA system requirements using inputs from MCAIR's propulsion system integration experts. We used this matrix to assess the relative significance of each major air induction system design feature on propulsion system characteristics or "qualities", including signature, performance, weight, cost, producibility and other factors. The results of this assessment were used to develop six high payoff inlet trade studies including: 1) MRF External Diffuser Design, 2) MRF and AMA Cowl Lip Design, 3) MRF and AMA Subsonic Diffuser Design, 4) MRF and AMA Engine Front Frame Design, 5) Inlet Material Selection, and 6) AMA Secondary Off-Take Design. The results of these trade studies, and the QFD matrix were then used to select the "best" air induction system configuration for each notional weapon system concept developed in Task I, based on weighting provided by MCAIR's propulsion system integration experts. To validate the QFD approach, the relative Takeoff Gross Weight (TOGW) impact of each system selection was also determined using TOGW sensitivities developed in previous system studies. The Task II study flowchart is illustrated in Figure 33.

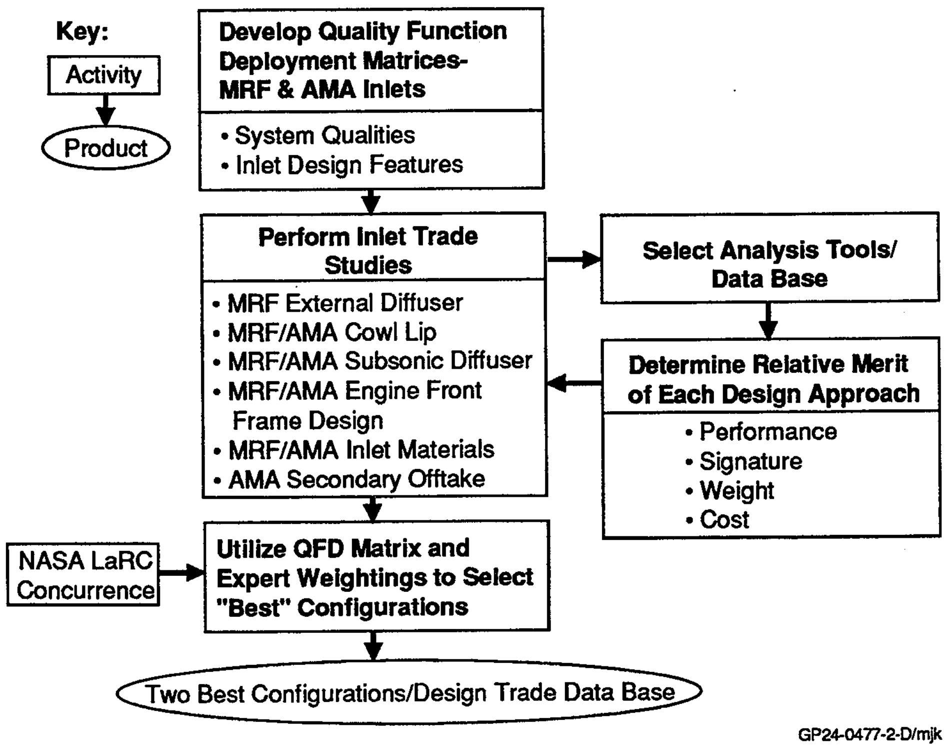


Figure 33. Task II – Trade Studies Study Plan

3.1 QUALITY FUNCTION DEPLOYMENT (QFD) MATRIX DEVELOPMENT

Quality Function Deployment (QFD) is a method being used increasingly in Concurrent Engineering (CE) to develop products and the supporting processes based on the following interpretation of QFD:

- Quality – What the user needs or expects.
- Function – How a set of needs/expectations are satisfied.
- Deployment – Making it happen.

QFD starts with the "Voice of the Customer (VOC)". In the ideal setting, the configuration development team gathers the end user's needs and expectations. The team has to carefully analyze these inputs to

avoid only providing what they expect or believe that the end user needs. Conceptual models can be used to help better understand how the user will evaluate the quality of the product.

The team then uses QFD as a planning tool to derive configuration specifications that will satisfy the VOC while remaining within practical resource and technology constraints.

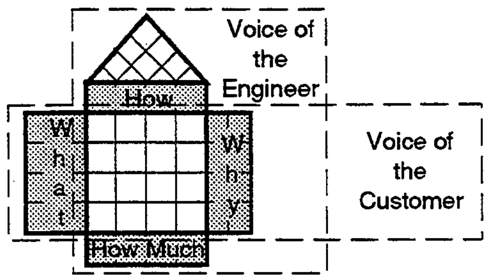
QFD facilitates CE by fostering a common understanding of user requirements and of the team's integrated approach to satisfying those requirements. QFD is generally associated with the matrix chart commonly known as the House of Quality, Reference 12. The QFD analysis is documented in a set of these charts, as illustrated in Figure 34. The use of a standardized graphical format enables the configuration development team to focus on the weapon system requirements and design features in a straightforward, unambiguous manner.

This study's QFD analysis is summarized in the matrix depicted in Figure 35. The "WHAT's", or overall air induction system "qualities" were defined by convening focus groups of MCAIR's MRF, AX and special program propulsion integration specialists and "mind-mapping", or "brain-storming" to determine the most important integration characteristics of insuring maximum weapon system effectiveness, and then assigning priority weightings (or "WHY's"), to each quality. The "HOW's", or air induction system major design features, were then defined by examining the air induction system concepts defined in Task I, and those of production (F-15, F-18), and prototype (YF-23, A-12) aircraft, identifying the system major components on both a functional and structural basis. The impact of each design feature on each system quality was assessed as being strong, moderate, weak or not applicable, and given a relationship weighting factor of 5, 3, 1 or 0. The relative significance of each design feature on the "total quality" of the air induction system, ("HOW MUCH"), was then rated by multiplying the system quality priority rating by the relationship weighting factor assigned to the design feature, and then summing that product for each quality in the matrix. The resulting sums for both the notional MRF and AMA weapon system concepts are listed at the bottom of each "HOW" design feature column.

In general, design features found to be significant for the AMA were also significant for the MRF, with a few notable exceptions. These exceptions were largely due to the differences in the quality prioritization developed by the advanced design propulsion system integration experts. For instance, the highest priorities assigned to the MRF propulsion system were transonic maneuverability (high recovery/low distortion), low weight, high supportability, and low cost. In contrast, AMA priorities were low radar cross section, static/takeoff and landing performance (high recovery/low distortion), low weight and anti-ice or ice protection technology. Unlike previous air induction system studies of this nature, inlet aerodynamic performance issues did not dominate the design prioritization. This pattern has also proven to be the case in real world design synthesis efforts.

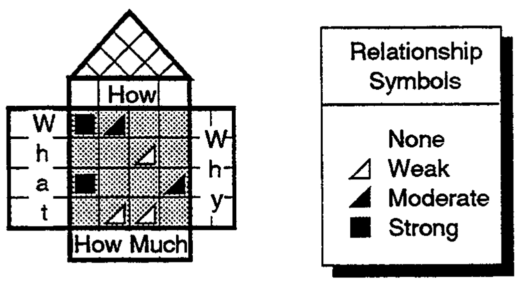
The design features of greatest significance to MRF propulsion system quality are highlighted in Figure 35, and include the inlet external diffuser (compression ramps, bleed system, etc.), the inlet cowl lip, the subsonic diffuser obscuration, the engine front frame configuration, and the diffuser wall materials (metal, carbon-epoxy, Radar Absorbing Material, Radar Absorbing Structure). The significant AMA design features include the inlet cowl lip, the subsonic diffuser obscuration, shaping (offset) diffuser vane integration, the engine front frame configuration, and the secondary airflow offtake configuration.

The final step in developing the QFD matrix was to assess the potential for strong interactions between significant design features. Strong interactions are noted by the symbols inserted in the QFD matrix "rooftop". Strong interactions exist between the cowl lip design and cowl lip material integration, and the diffuser obscuration shaping (offset), diffuser vane integration, the front frame design, and the secondary airflow offtake configuration. All of these design features must be addressed in any trade study which addresses weapon system total quality, with special attention to adverse feature interactions which tend to drive the overall inlet design in different directions.

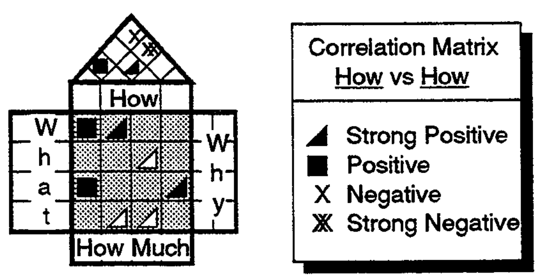


Step 1
The team collects the VOC, or Whats, from all possible sources, including the contractual statement of work. The Whats are weighed to reflect the customer's perception of importance. These weights, along with other relevant source data, are referred to as the Whys.

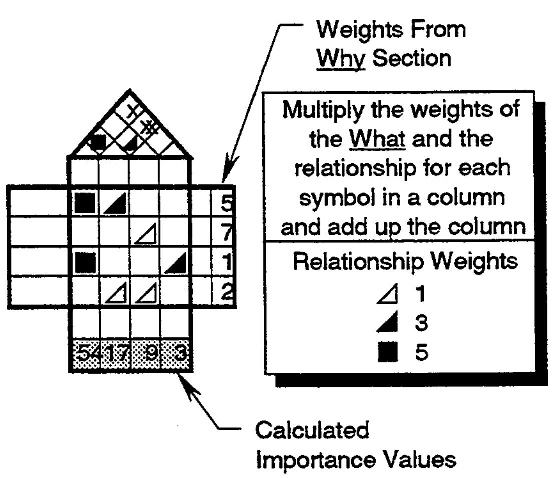
Step 2
The team then develops a baseline concept that should satisfy the customer's requirements. The details of the concept are referred to as the Hows and How Muches.



Step 3
The baseline concept is then analyzed to determine if it satisfies the Whats. The team determines the relationship, if any, of each How/How Much pair to each of the Whats.



Step 4
The Hows are correlated to one another to determine conflicts. Trade studies are performed to identify the optimal tradeoffs.



Step 5
The How Muches are augmented with calculated values, which provide implementation priorities and areas of special concern.

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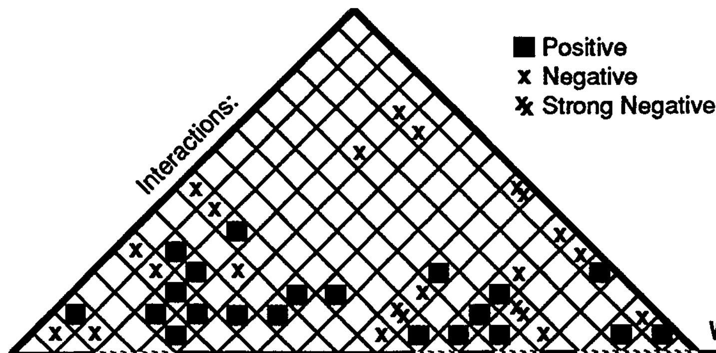
Figure 34. Quality Function Deployment (QFD) Analysis



Relationships:
None 0
Weak 1
Moderate 3
Strong 5

What's: / How's:	Forebody Shape	Forebody BLM	Inlet Ext. Diffuser	Inlet Lip Config.	Inlet Contraction	Inlet Location	Inlet BLM	Aux. Inlet Config.	Diffuser Bifur.	Diffuser BLM	Diffuser Obscuration	Diffuser Vane Config.	Engine Front Frame	Anti-Ice Tech.	Secondary Offtake	Cowl/Ramp Lip Mat'l	Diffuser Wall Mat'l	AMA System Weighting	MRF System Weighting
Airframe Signature - Radar Cross Section	3	3	3	3	0	3	3	0	3	0	5	5	5	0	3	5	5	10	7
Airframe Signature - Infrared	0	0	0	0	0	0	0	0	0	0	1	1	1	0	5	0	0	8	0
Int. Performance - Static (Takeoff/Landing)	1	1	1	5	5	1	0	5	3	3	3	3	3	0	0	0	0	10	1
Int. Performance - Post-Stall (Mach=0.3)	3	1	1	5	5	5	0	5	1	3	3	3	3	0	0	0	0	0	7
Int. Performance - Trans. Maneuver (Mach=0.9)	5	3	1	3	3	5	1	5	3	3	3	3	3	0	0	0	0	5	8
Int. Performance - Supersonic Cruise	5	5	5	3	3	5	5	1	1	3	3	3	3	0	0	0	0	0	6
Inlet Drag - Subsonic Cruise	1	1	3	3	3	1	1	0	0	0	0	0	0	0	1	1	1	3	3
Inlet Drag - Supersonic Dash	1	3	5	5	5	3	3	0	0	0	0	0	0	0	1	1	1	0	5
Inlet Icing Performance	0	0	1	5	0	0	0	0	0	0	0	5	5	5	3	5	1	8	1
Inlet System Weight	0	1	3	1	1	1	3	3	5	1	5	3	3	1	3	3	5	9	9
Inlet Airflow Growth Potential	1	0	3	5	5	1	0	0	5	0	3	0	0	0	3	0	0	6	6
Inlet Supportability	0	3	0	1	0	1	3	1	0	3	0	3	3	3	1	5	5	5	8
Inlet Productivity and Cost	0	3	3	3	0	0	3	3	3	3	5	3	5	3	3	3	5	5	10
How Much: AMA	74	97	N/A	203	113	88	95	122	N/A	84	191	200	210	79	162	160	156		
How Much: MRF	127	164	177	219	155	168	158	151	166	129	214	187	207	68	N/A	145	179		

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Figure 35. MRF and AMA Air Induction System QFD Matrix

3.2 TRADE STUDY ISSUES

To address the significant air induction system design features identified in the Task II QFD analysis, six trade study issues were identified and a six-part study plan was developed. The Task II trade study issues, parametrics, figures-of-merit, and study methodologies addressed in this program are summarized in Figure 36.

The first trade study examined the impact of the inlet external diffuser, or compression ramp configuration, on inlet recovery, drag, weight and RCS for the MRF configurations. The second trade study examined the impact of the cowl lip cross-sectional shape and planform on inlet and distortion performance and RCS, for both the MRF and the AMA configurations. The MRF cowl lip performance characteristics were evaluated at Post-Stall maneuver conditions, while the AMA cowl lip performance characteristics were evaluated at static and low speed conditions, (carrier takeoff and landing). The third trade study examined the impact of the subsonic diffuser configuration on inlet performance, distortion, RCS, and weight. For the MRF configurations, two bifurcated diffusers were compared to a single duct inlet, with and without a serpentine obscuration feature. For the AMA configurations, three serpentine diffusers of varying length/diameter ratio and obscuration were compared.

Section	Trade Issues	Aircraft	Parametrics	Figures-of-Merit	Methodology
3.2.1.	Inlet Ext. Diffuser	MRF	Ramp Configuration	Supersonic Recovery, Drag, Weight, RCS	Data Base Interrogation, PSIP Perf. Analysis
3.2.2.	Inlet Cowl Design Lip	MRF (Post-Stall)	Lip Radii, Shielding, Aux. Inlet Area, Lip Material	Subsonic Recovery, Distortion, RCS	Data Base Interrogation, 2D MOM RCS Analysis, PSIP Perf. Analysis
		AMA (Takeoff/ Bolter)	Lip Radii, Sweep Aux. Inlet Area	Static Recovery, Distortion, RCS	
3.2.3.	Subsonic Diffuser Config.	MRF	Single vs. Bifurcated, Offset	Recovery, Weight, RCS	Data Base Interrogation, NASTD CFD Analysis, CADDSCAT/ CAVERN RCS Analysis
		AMA	Offset, L/D	Recovery, Weight, RCS	
3.2.4.	Engine Front Frame Config.	MRF & AMA	Baseline and Level I,II, III, Waveguide vs LOS	Recovery, Weight, RCS, Anti-Icing, Cost	Engine Co. Subcontract
3.2.5.	Inlet Diffuser Wall Material Selection	MRF & AMA	Metal, Composite, RAM, RAS	Weight,RCS, Cost	Data Base Interrogation, CADDSCAT/ CAVERN RCS Analysis
3.2.6.	Secondary Airflow Offtake	AMA	Configuration, Location	Weight, $\Delta P/P$, RCS	Data Base Interrogation

Code definitions:
- PSIP – Propulsion System Installed Performance (Thrust-Drag Accounting Code)
- 2D MOM – Two-Dimensional Method-of-Moments Electromagnetic Scattering Code
- NASTD – Navier-Stokes Time-Dependent 3D Computational Fluid Dynamics Code
- CADDSCAT – Three-Dimensional, Physical Optics-Based Electromagnetic Scattering Code
- CAVERN – Three-Dimensional, Physical Optics/Modal Solution-Based Cavity Electromagnetic Scattering Code

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Figure 36. Trade Study Issues, Parametrics and Figures-of-Merit

The fourth trade study examined the impact of the engine front frame configuration on front frame RCS, anti-icing potential, recovery, weight and cost. This study was performed using data provided under subcontract by Pratt and Whitney Aircraft, and under a complementary IRAD study performed by General Electric's Aircraft Engine Group. The fifth trade study examined the inlet cowl lip and subsonic diffuser wall material selection from a weight, performance and cost standpoint. Material candidates examined included metal, carbon-epoxy composite, parasitic single and multi-layer RAM coatings, and complete RAS structures. The sixth and final study examined the impact of the ejector nozzle secondary airflow offtake and delivery system configuration on ejector nozzle secondary airflow pressure ratio and ejector nozzle performance, and system RCS.

All the trade studies were accomplished using MCAIR's advanced design propulsion integration methods including empirically-based design computer programs, computational fluid dynamics analyses, and interrogation of a large number of technical reports from open literature and MCAIR's advanced design and technology development programs.

3.2.1 Inlet External Diffuser Trade Study – The supersonic and transonic performance of any high performance fighter aircraft is greatly influenced by the configuration of the external diffuser or supersonic ramp configuration. This system provides supersonic diffusion of the ingested flow, normal shock/boundary layer interaction control, and angle-of-attack shielding of the cowl lip to improve transonic maneuverability, depending on the location and orientation of the compression ramps. The more sophisticated the external diffuser design becomes, the more efficient the inlet's supersonic recovery, Reference 13. This efficiency comes with a price, however, in drag, weight, and potentially Radar Cross Section (RCS).

The notional MRF supersonic requirements include a V_{max} of Mach 1.6, and an 0.8 to 1.6 Mach No. acceleration requirement of 60-seconds. The notional requirements do not, however, include supersonic cruise capability. The supersonic acceleration requirement can be a significant factor in propulsion system scaling, depending on the selected wing loading and aircraft thrust/weight assumptions.

The three notional MRF concepts incorporate different external diffuser concepts and forebody integrations. The MRF 1006, Figure 13, incorporates twin side-mounted 7° caret inlets, while the MRF 1209, Figure 17, incorporates a chin-mounted LO pitot normal shock inlet. The MRF 2001, Figure 20, incorporates twin leading edge extension-shielded 2° asymmetric caret/normal shock inlets. The supersonic theoretical shock structure recovery projected for these three concepts is presented in Figure 37. All three concepts have approximately the same shock structure recovery (pressure recovery at the inlet throat) up to Mach 1.3, the point where the caret inlet oblique shock attaches to the ramps. At Mach 1.6, the caret inlet is significantly more efficient than the normal shock inlets giving a 2.8% recovery advantage, which translates into a 3.4% net thrust advantage.

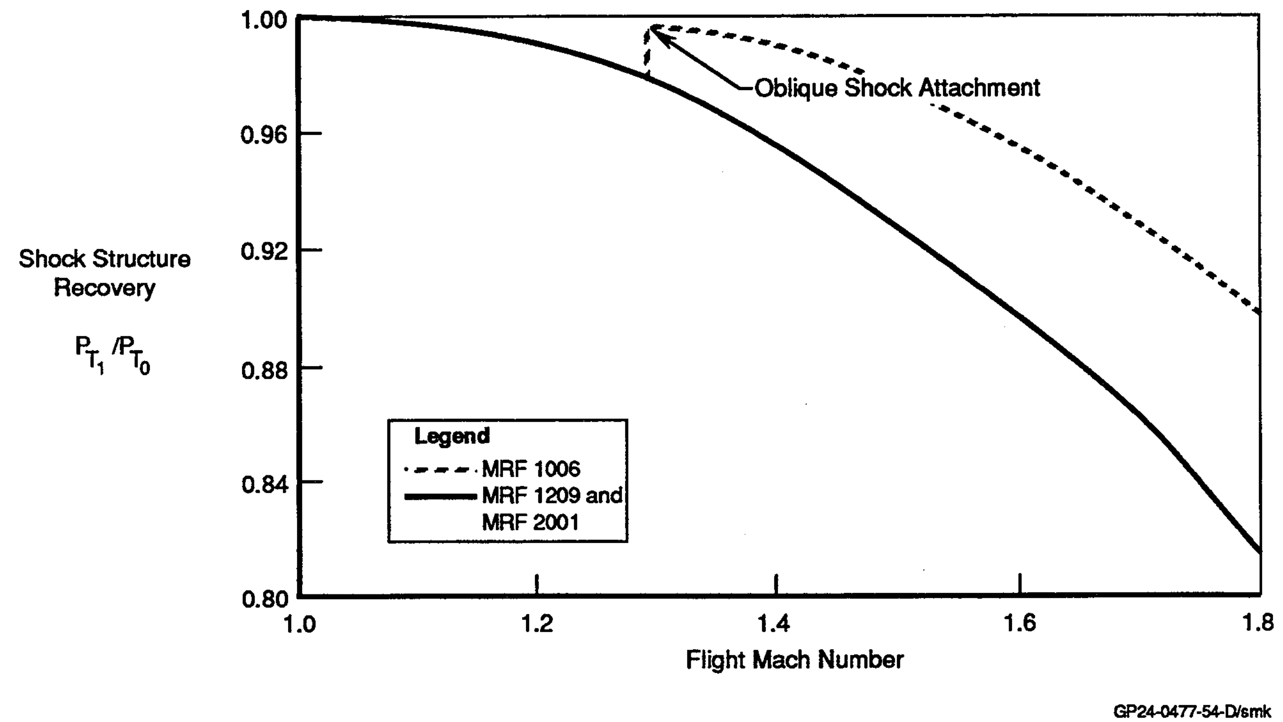

Figure 37. MRF Supersonic External Diffuser Recovery

This performance increase comes at the price of increased capture area, Figure 14. The MRF 1006 inlets are 15% larger than the MRF 2001 inlets and 23% larger than the MRF 1209 inlets. This larger capture area results in higher throttle dependent drag at both subsonic and supersonic conditions at reduced mass flow ratio for a fixed inlet. Using the inlet drag database developed in Reference 14, subsonic and supersonic throttle-dependent drag characteristics were estimated for the three MRF configurations. MRF spill inlet drag characteristics are illustrated in Figure 38 and 39. At the Battlefield Air Interdiction (BAI) mission ingress, the inlet MFR is approximately .6, resulting in a 1.5% thrust penalty. This penalty may be alleviated by an airflow bypass system, Reference 15.

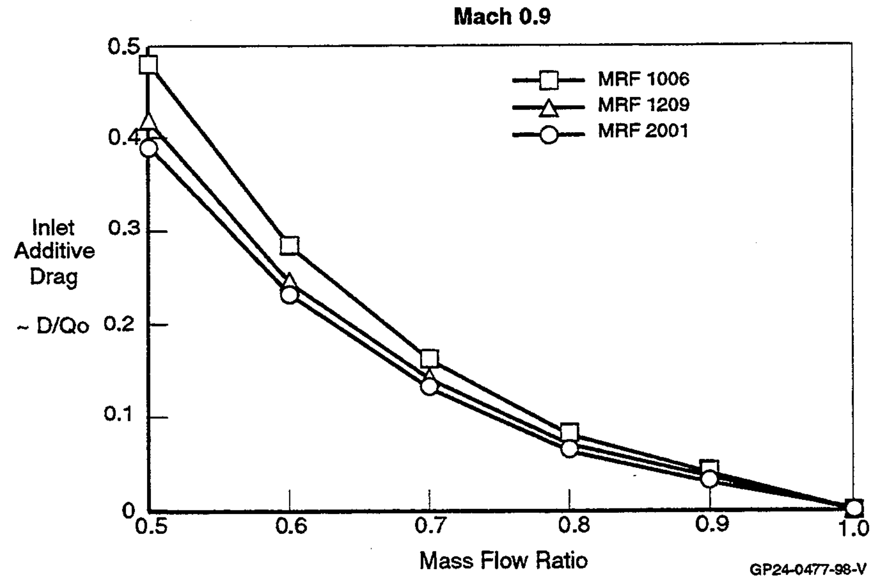

Figure 38. MRF Subsonic Drag Trends

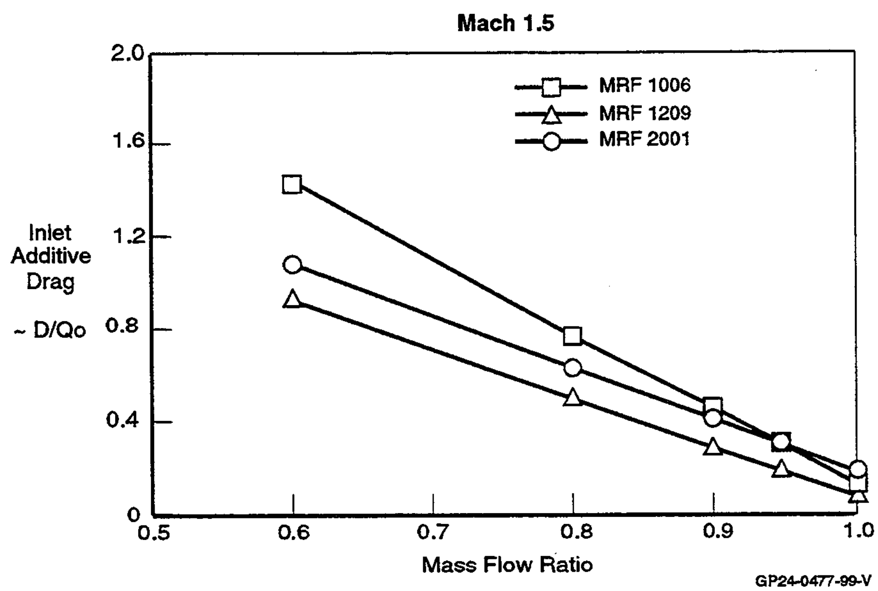

Figure 39. MRF Supersonic Drag Trends

The external diffuser design also has an impact on weight and inlet bleed requirements. MRF inlet capture areas, external diffuser wetted areas, and edge geometries are summarized in Figure 40. The external diffuser wetted areas drive structural weights. Each square foot of wetted area requires an inner and outer skin and enclosed formers at approximately 4 lbs./sq. ft., if constructed from Carbon-Epoxy (C-E) composite. This results in a 7 lb. weight penalty for the MRF 1006, and a 15 lb. penalty for the MRF 2001. The higher wetted area for the MRF 2001 is a result of the use of a swept rather than a serrated cowl lip geometry, and the consequent incorporation of an extended throat box. This geometry also results in normal shock contact with all four walls of the inlet aperture during supersonic operation. This requires somewhat higher inlet bleed, and allows somewhat reduced stable range than "open-throat" designs, due to the extended longitudinal distance the shock must traverse in the inlet to create subsonic spill area. Using the

Aircraft	Capture Area	Wetted Area	Ramp/Cowl Sweep and Elevation Angles	Number of Visible Edges	Ramp/Cowl Sealed Edge Length L/λ*
MRF 1006	8.0 ft^2	8.6 ft^2	35° Sweep 0°/31° Elevation	8/2	4.8/11.2
MRF 1209	6.5 ft^2	6.9 ft^2	35° Sweep 0°/45° Elevation	2/2	5.7/10.0
MRF 2001	6.9 ft^2	6.9 ft^2	32.5° Sweep 0°/52.5° Elevation	2/2	7.4/7.4

*At 3 Ghz

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Figure 40. MRF Inlet Aperture Characteristics

bleed criteria developed in Reference 16, and assuming a constant bleed requirement for an equivalent wetted perimeter to capture area ratio, at Mach 1.6 the MRF 2001 requires 8% of inlet capture airflow in ramp and throat bleed vs. 4.5% bleed for the MRF 1209, and 2% or less for the MRF 1006.

The number of edges used in the inlet aperture is another consideration in the selection of the external diffuser. In general, the more edges required to enclose the inlet capture, the higher the resultant RCS. The incorporation of a compression ramp can add an edge, which a normal shock inlet does not have. The MRF 1209 incorporates just four long edges in its design vs. six for the MRF 2001 and ten for the MRF 1006, (assuming the flush boundary layer diverters incorporated in these aircraft can be effectively hidden nose-on).

The selection of an external diffuser configuration is a function of the prioritization of supersonic performance, subsonic drag, weight and RCS. A high performance external diffuser will improve inlet performance substantially above Mach 1.4 and will reduce or eliminate inlet ramp/splitter boundary layer bleed requirements by minimizing the terminal normal shock Mach No. This performance must be traded off, however, against the increased drag, weight and RCS potential. For an aircraft with V_{max} requirements above 1.6, the use of an external diffuser is probably not optional. For a transonic fighter such as the MRF, however, the normal shock inlet may offer better system integration potential, due to lower weight and drag.

3.2.2 Inlet Cowl Lip Trade Study – The inlet static, subsonic and maneuvering recovery and distortion, additive drag, and inlet RCS are all fundamentally dependent on cowl lip design. The inlet cowl lip design determines the inlet internal contraction ratio, and to a large extent, the inlet throat inflow properties, including the presence and extent of any flow separation.

Typical cowl lip geometries are depicted in Figure 41. At MCAIR, cowl lip cross-sections are often drawn as truncated ellipse, in which a circle of lip radius "R" is drawn at the intended highlight station, and then an ellipse is drawn around the circle such than the ellipse is tangent at an angle from 0° to 30° off vertical. Typical geometries used in supersonic fighters have lip fineness ratios of 4.0 or greater, and lip thickness ratios of 1.5 to 3.0. Subsonic attack aircraft often use blunter lip geometries and less eccentric ellipses, with fineness ratio of 2.0 to 3.0 and thickness ratios of 1.0 to 2.0. Lip camber is often introduced to align the cowl lip with the incoming flowfield. For a supersonic diffuser concept such as the MRF 1006, the lip camber angle is set at the ramp compression angle, in this case 7°. Lip camber is often taken over a longer distance than the ellipse major axis.

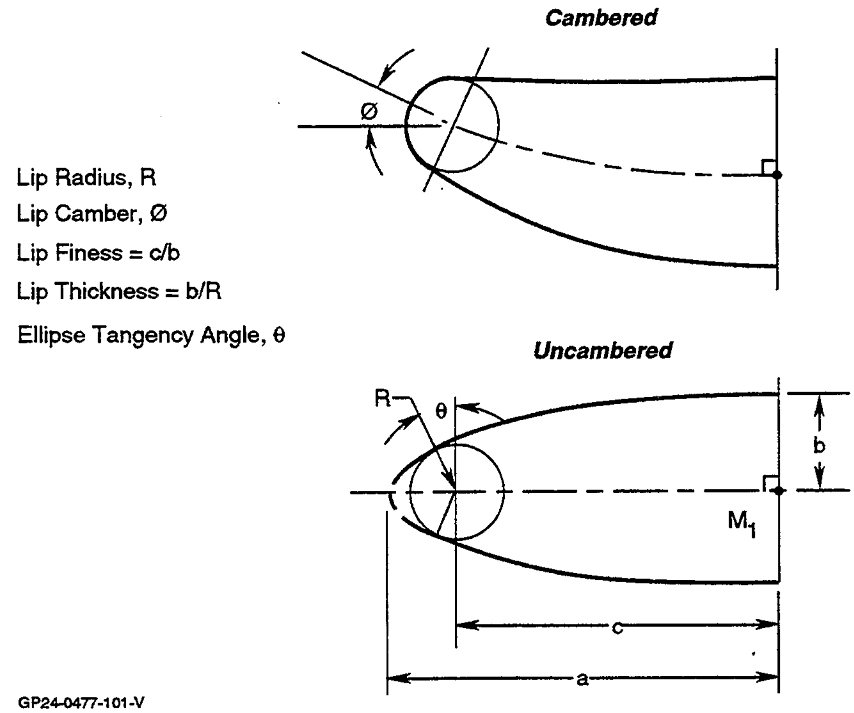


Figure 41. Cowl Lip Cross-Section Geometry

The most important aerodynamic design variables in lip cross-sectional geometry are the lip local radius, R, and the total lip contraction, or internal contraction ratio. Lip contraction is determined by the lip radius and the lip thickness ratio. Lip RCS is determined entirely by the lip radius. Typical fighter and attack aircraft lip radii range from very sharp, (.10"), to quite blunt, (3.0"). Increasing lip radius improves inlet static and maneuvering performance, particularly at post-stall conditions, but increases inlet drag, particularly at supersonic conditions, and increases inlet RCS. Inlet cowl lip RCS characteristics are a function of lip radius and treatment for both notional MRF and AMA RCS frequency regions of interest. RCS considerations drive metal cowl lip designs to very small radii to reduce nose-on RCS sidelobe levels. Radar absorbing materials are a requirement for systems requiring either inlet lip radii greater than .2", or low RCS at frequencies below 3 GHz.

The effect of lip radius and sweep on inlet static recovery and distortion were experimentally investigated by MCAIR in early 1992, Figure 42. In general, increasing lip radius and decreasing cowl sweep angle tend to increase recovery and reduce distortion. Decreasing lip radii to below 0.5" results in recovery losses 5% to 10% lower than these levels, with even larger distortion levels. Inlet lip induced losses at static conditions are largely due to flow separation on the cowl lip itself. This flow separation is due to the extreme flow angles (90°-180° AOA) on the cowl induced by the inlet suction. Flow Mach numbers can exceed 1.0 locally with extremely high radial turning rates which cannot be sustained, causing flow separation. The most effective way found to reduce these losses at static conditions is to reduce the lip aerodynamic loading by reducing the throat Mach number. This is accomplished by incorporating a second or auxiliary static inlet in the diffuser downstream of the main inlet. Auxiliary inlets can be quite effective in reducing inlet recovery losses, even for very blunt lip, high contraction inlets such as the AV-8B Harrier V/STOL aircraft, Figure 43. Auxiliary inlets can have even more dramatic results on sharp lip inlets, such as the .2" lip radius axi-inlet tested by MCAIR in 1984, Figure 44. Auxiliary inlets can be hidden, from an RCS perspective, when not in operation by use of LO doors and seals, and placement on the aircraft in unobtrusive areas, such as the aircraft topside. For these reasons, incorporation of an auxiliary inlet in an aircraft with stringent static or low speed inlet performance requirements, such as V/STOL aircraft, or an AMA aircraft, can be beneficial.

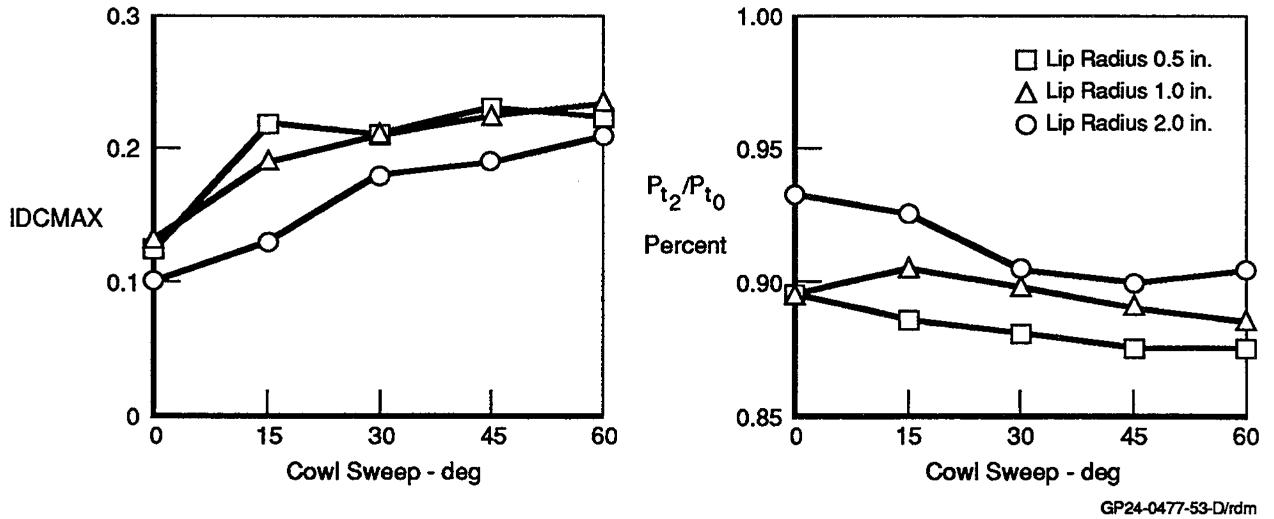


Figure 42. Effect of Cowl Lip Radius and Sweep on Static Recovery and Distortion

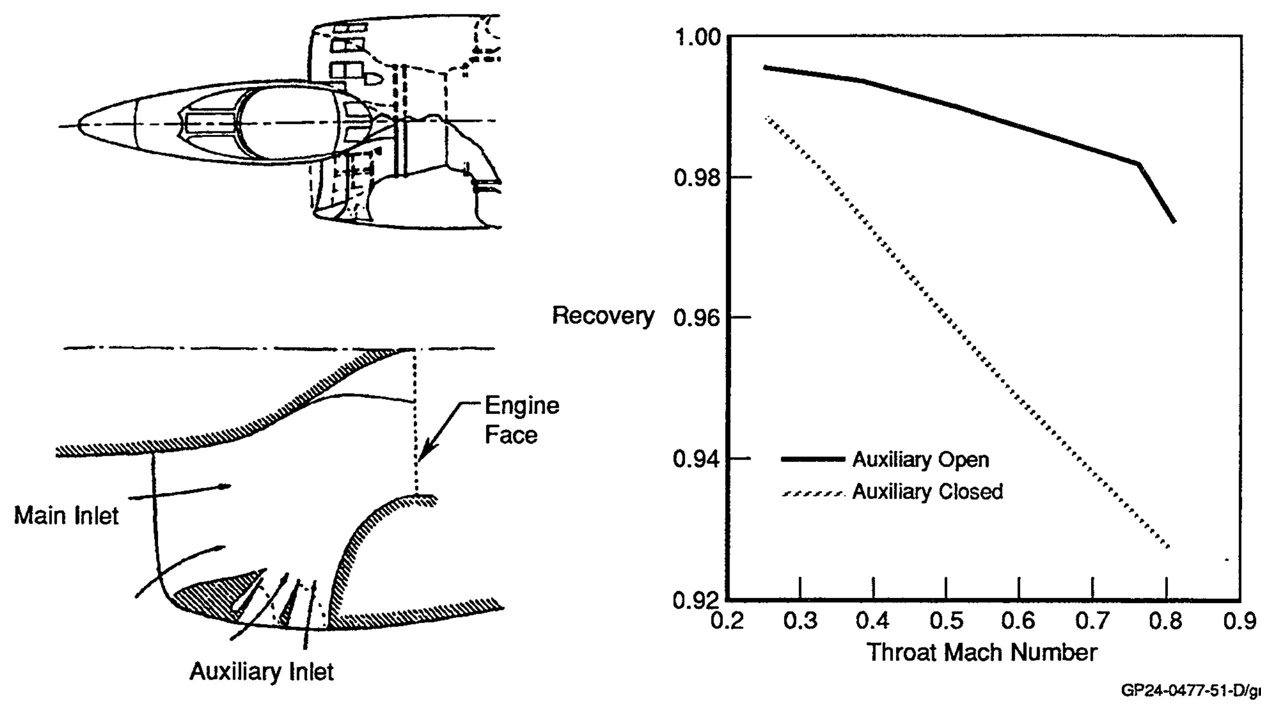


Figure 43. Effect of Auxiliary Inlet Integration on AV-8B Harrier Inlet Recovery

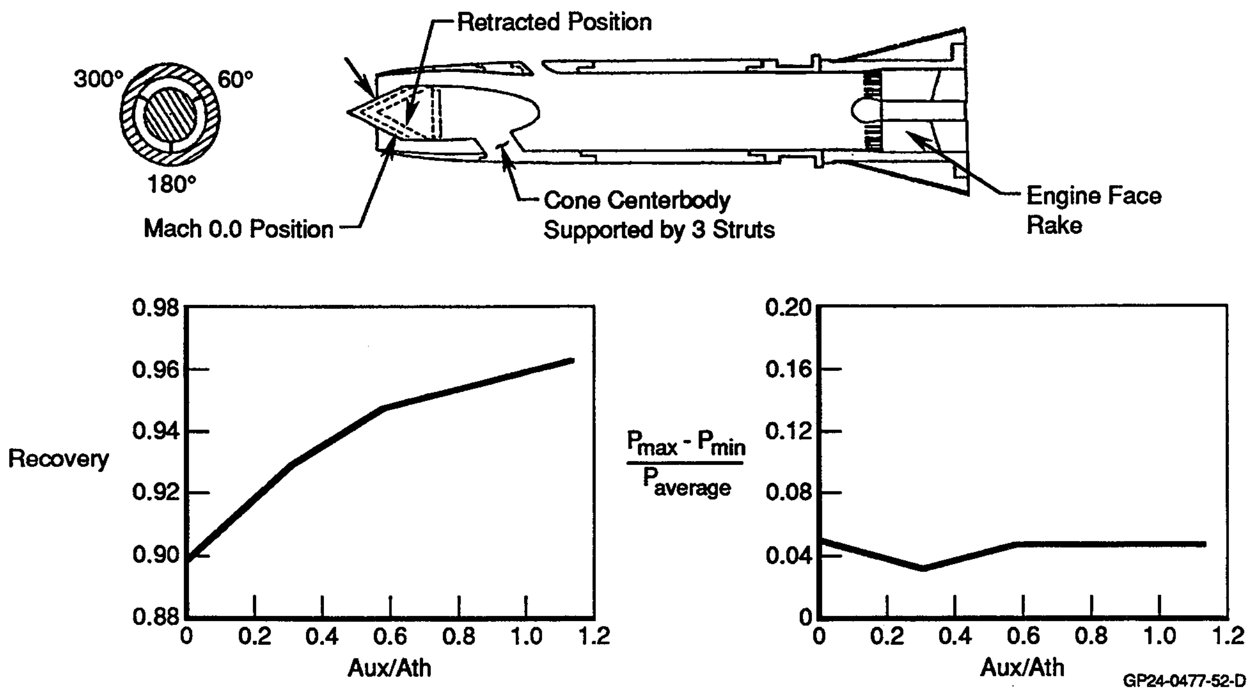


Figure 44. Effect of Auxiliary Inlet Area on Sharp Lip Inlet Recovery at Mach 0.25

Lip radius can be effective in reducing losses in transonic maneuvering flight, but may be less important than other factors, such as local angle-of-attack, Reference 17. In wind tunnel testing conducted at NASA Lewis Research Center, it was found that deflection of the cowl lip of an overhead ramp inlet by as much as 40° downward can dramatically increase high AOA recovery, and reduce inlet turbulence levels, Figure 45. Lip angle-of-attack can also be reduced by effective AOA shielding of the inlet by the forebody, wing, or inlet compression ramps, Reference 18, Figure 46. These characteristics were confirmed for LO forebodies in 1986 by NASA and MCAIR, Reference 19.

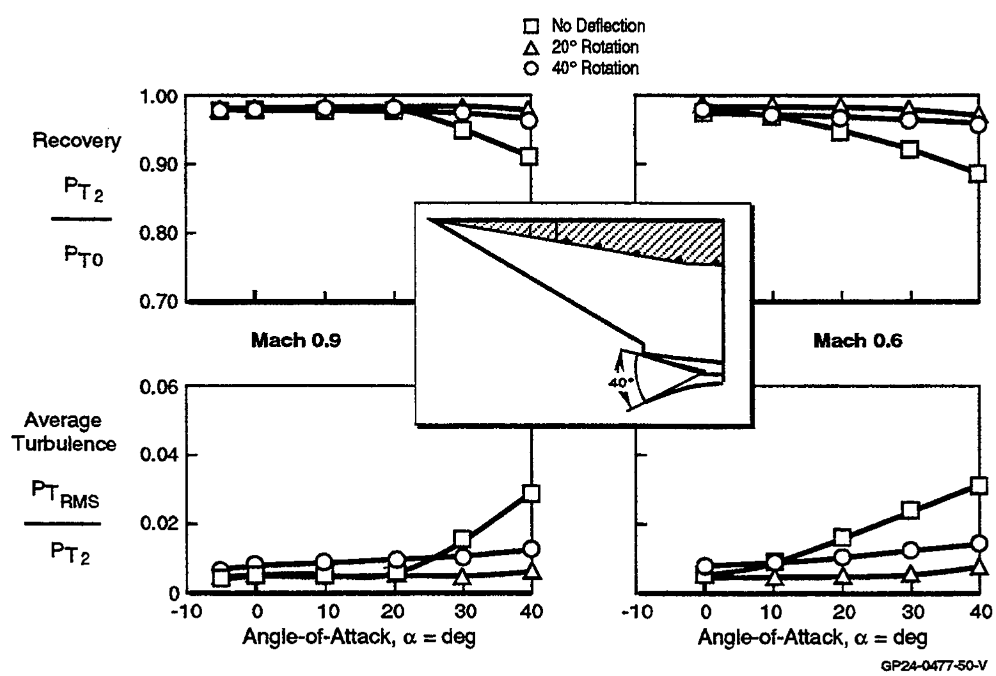


Figure 45. Effect of Cowl Lip Rotation on Transonic Maneuvering Performance

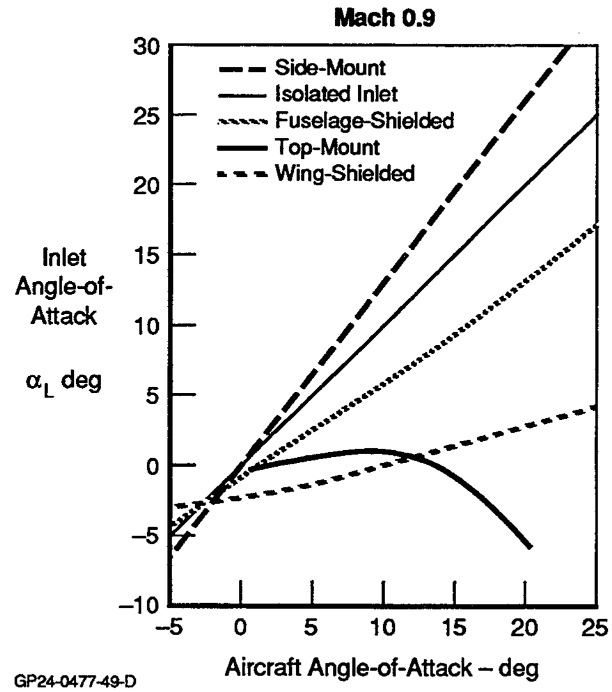


Figure 46. Comparison of Inlet Local and Aircraft AOA for Various Inlet Locations

A dramatic example of the effectiveness of wing shielding on inlet performance is shown in the inlet subsonic maneuvering experience envelope demonstrated by the F/A-18 fighter, Reference 20. This air induction system concept combines a blunt (2.0" radius) lower cowl lip with an inlet-shielding leading edge extension or "LEX" to provide extremely high maneuverability, Figure 47. The F-18 inlet design is fully compatible with the Post-Stall (PST) maneuvering envelope requirements postulated in Section 2.1, and presents an excellent starting point for an MRF PST inlet design.

High AOA, low speed inlet recovery was assessed for unshielded overhead ramp, side-mounted inlets such as the MRF 2001 and 1006 and compared to a forebody-shielded inlet such as the MRF 1209, using local angle-of-attack data from, Reference 18, and MCAIR High AOA isolated inlet data taken at Mach .25, Figure 48, for sharp-lipped inlets. The benefit of shielding on inlet recovery at 60° AOA is dramatic. Modifying the MRF 1209 inlet through use of a variable cowl lip or auxiliary inlet may allow post-stall recovery levels as high as transonic maneuver recovery.

Inlet cowl lip design characteristics for low RCS, and good static and maneuvering performance run in opposite directions. Low RCS design requires either very sharp lip contours and high sweep angles, or extensive material integration. Good inlet static and low speed performance requires large, blunt cowl lips with low sweep angles, or, incorporation of auxiliary inlets. Subsonic and transonic maneuvering performance benefits from lip bluntness and inlet lip angle-of-attack shielding, either through variable cowl angle, or inlet AOA shielding. Because of these incompatibilities, an effective air induction system design cannot depend on a cowl lip design compromise alone, but must rely on one of a number of emerging technologies to exhibit both low RCS design and good performance. RAS edges can provide good low RCS with reasonable large lip radii, but must be designed to withstand bird strike and be compatible with anti-icing technology for Navy applications. Auxiliary inlets can be designed to unload the inlet lip at static and maneuver conditions, but must be designed to meet stringent aircraft moldline and subsonic diffuser LO integration concerns. Finally, effective AOA shielding and LO-compatible mechanically variable or deformable material-based cowl lip structures may allow PST maneuverability with uncompromised signature and transonic performance.

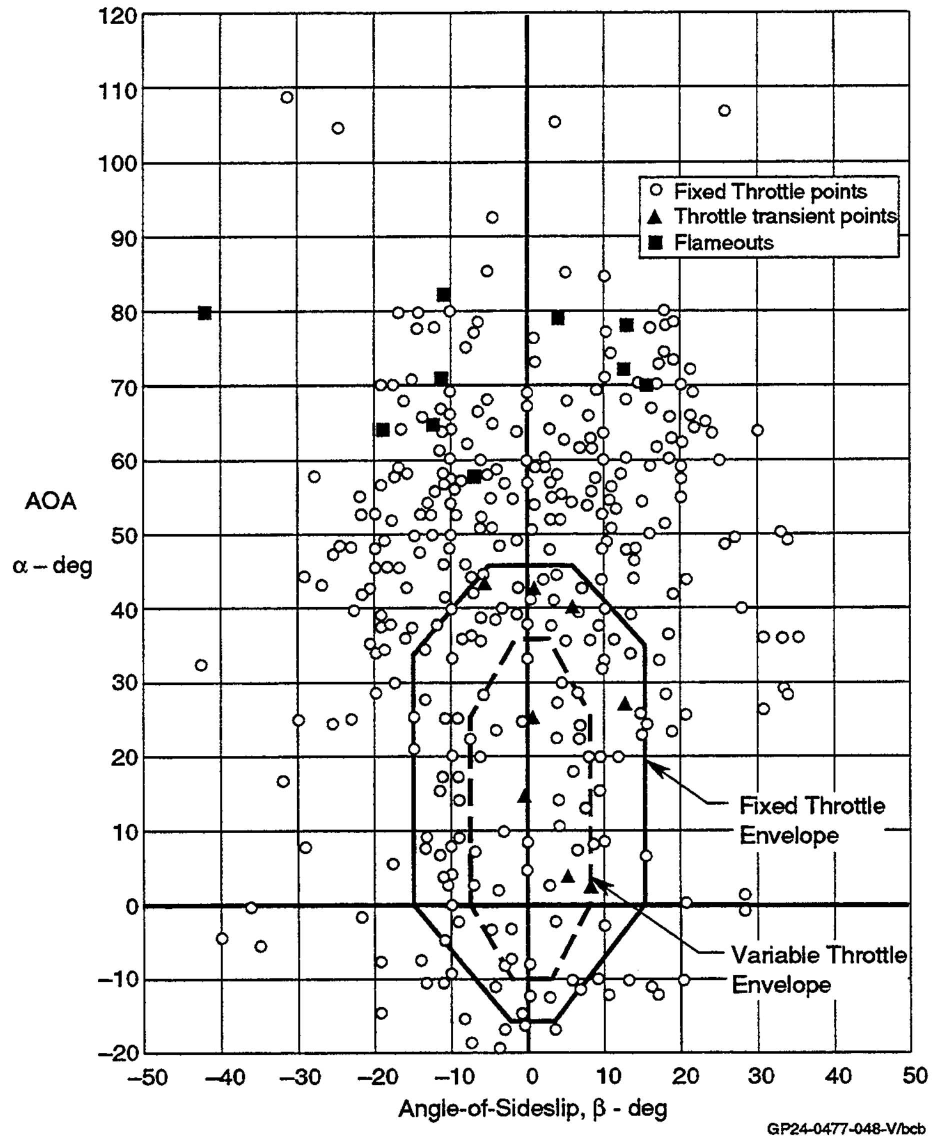


Figure 47. F/A-18A/F404 Subsonic Maneuvering Experience

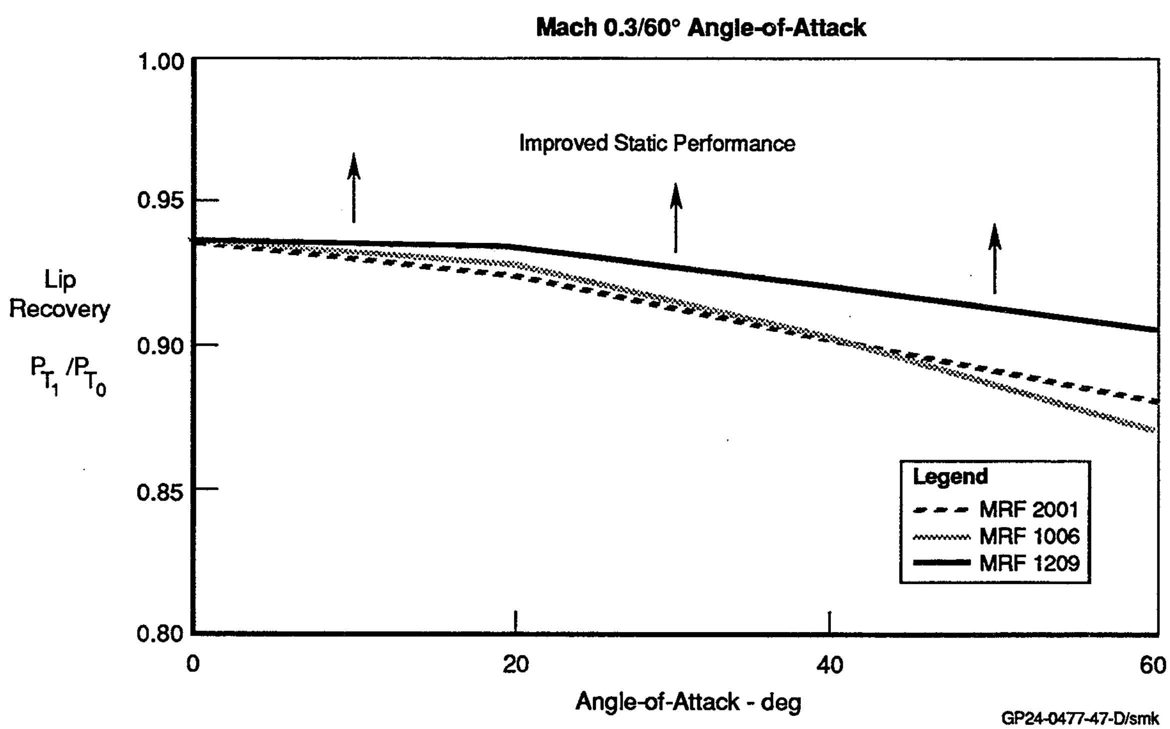


Figure 48. MRF Post-Stall Inlet Recovery Predictions

3.2.3 Subsonic Diffuser Configuration Trade Study – The inlet subsonic diffuser transports the captured engine airflow from the inlet throat while reducing the flowfield Mach No. from ~ .76 (95% of critical – Mach 1.0 – airflow) to ~ .5 at the compressor face. Subsonic diffusers have been relatively easy to design for past fighter and attack aircraft, given enough volume and length in the airframe to maintain a straight, uniform, measured increase in duct cross-sectional area. The advent of low observable requirements has increased the difficulty and development risk of the subsonic diffuser design from a relatively low risk to the highest risk in the air induction system integration. This is because the engine compressor face, if unshielded from view, can easily have a higher RCS than the rest of the aircraft. The main objective in LO subsonic diffuser has become to provide engine face obscuration, either through offset, incorporation of diffuser vanes, or through use of an advanced LO front frame.

While the need for obscuration has forced diffuser designers to introduce offset or vanes, or both to the duct, the need for high recovery, low distortion airflow delivery to the engine compressor has remained. The biggest danger to diffuser aerodynamic performance is the potential for diffuser wall separation which is large enough to disrupt the diffuser flow, cause unsteadiness in the flow, or propagate into the engine face before reattachment can occur, resulting in large spatial variations in compressor face total pressure. If these steady-state pressure variations are accompanied by high levels of turbulence, high “dynamic distortion” can cause compressor stall.

Inlet offset in “conventional” aircraft can occur both laterally and vertically, but is usually predominantly in one direction. These ducts, here referred to as “single-offset” ducts, have been studied extensively in a Ref.(s) 11, 21, 22, 23 and 24, to determine the aerodynamic limits of wall-turning angle and boundary layer control for highly offset geometries. More recent diffuser studies for LO aircraft have concentrated on “double-offset” ducts which are offset “in” and then “out” either vertically or laterally to obscure line-of-sight of the engine face via the intervening “hump”. These ducts are referred to as “serpentine” ducts, and may include offset in the plane 90° from the double offset plane.

The aerodynamic risk of a diffuser may be assessed by cross-plotting its area ratio and average wall angle (including diffusion and turning), Figure 49. The F/A-18 and six concept diffusers characteristics are plotted on this chart which also includes empirically-assessed limits for first, reattaching stalls, and for more significant or "appreciable" stalls. This chart, developed in Ref. 11 for single offset diffusers, was applied to the MRF 1006 and 2001 bifurcated diffusers by considering one half the duct and calculating the hydraulic diameter (71% of the actual diameter) for all L/D and Δ/D ratios. The MRF 1209 and the AMA configurations were assessed by considering the "in" and "out" offsets, ("S1" and "S2") separately. All diffusers configured for the study fall in the region below the line of first stall with the exception of the MRF 2001 bifurcated diffuser, which is predicted to have a significant risk of stall. Subsequent Computational Fluid Dynamic (CFD) analysis of the this diffuser, using MCAIR's NASTD 3D/Navier-Stokes code, Figure 50, indicates that such a stall does not exist, and that this correlation may be conservative for bifurcated diffusers.

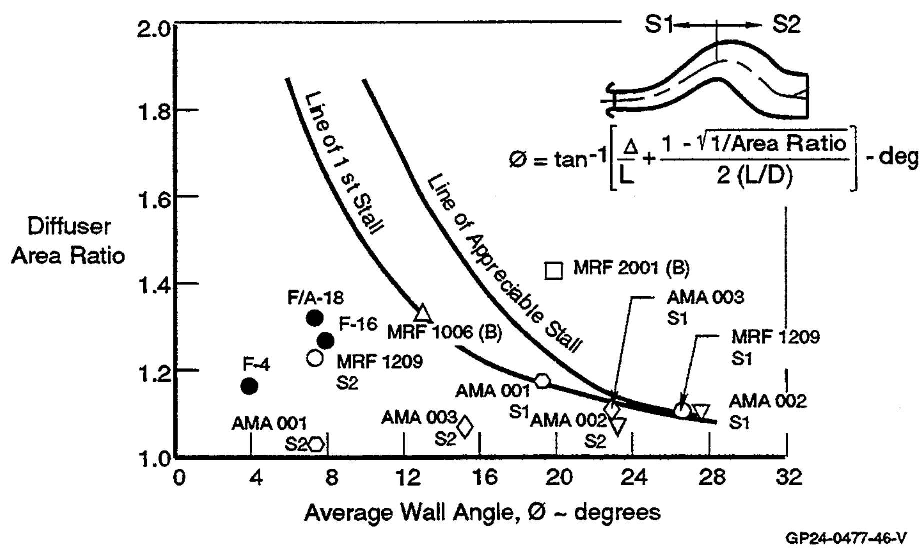


Figure 49. Subsonic Diffuser Aerodynamic Risk

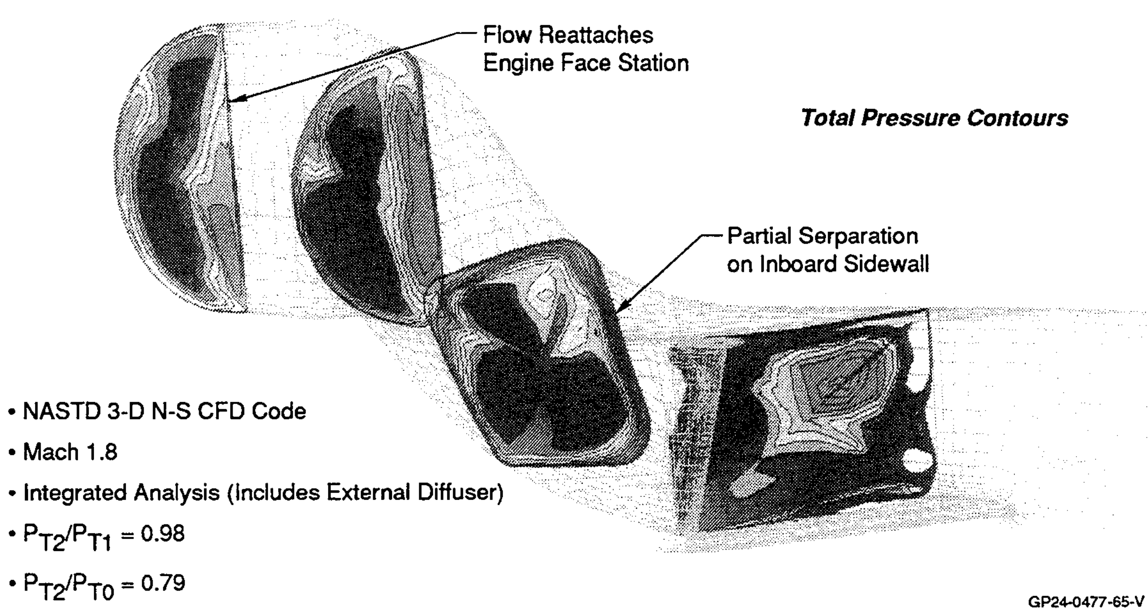


Figure 50. MRF 2001 Diffuser CFD Analysis

MRF and AMA diffuser pressure recovery characteristics were predicted using the correlations in Ref. 11. These estimates were made by calculating a diffusion loss based on equivalent conical diffuser angle, Figure 51, and the multiplying by an offset loss factor, based on the three-dimensional offset divided by the diffuser length, Figure 52. The diffuser offset loss factor correlation is based on a number of diffusers with relatively low aspect ratio, (turning cross-section height/width), and high losses for relatively small offsets compared to the serpentine ducts configured for this study. MCAIR data from experimental studies of highly offset, Gerlach-shaped serpentine diffusers have been compared to NASTD 3-D Navier-Stokes CFD analysis, and the Ref. 11 offset loss correlations. Both analysis were found to be conservative, Figure 53, with

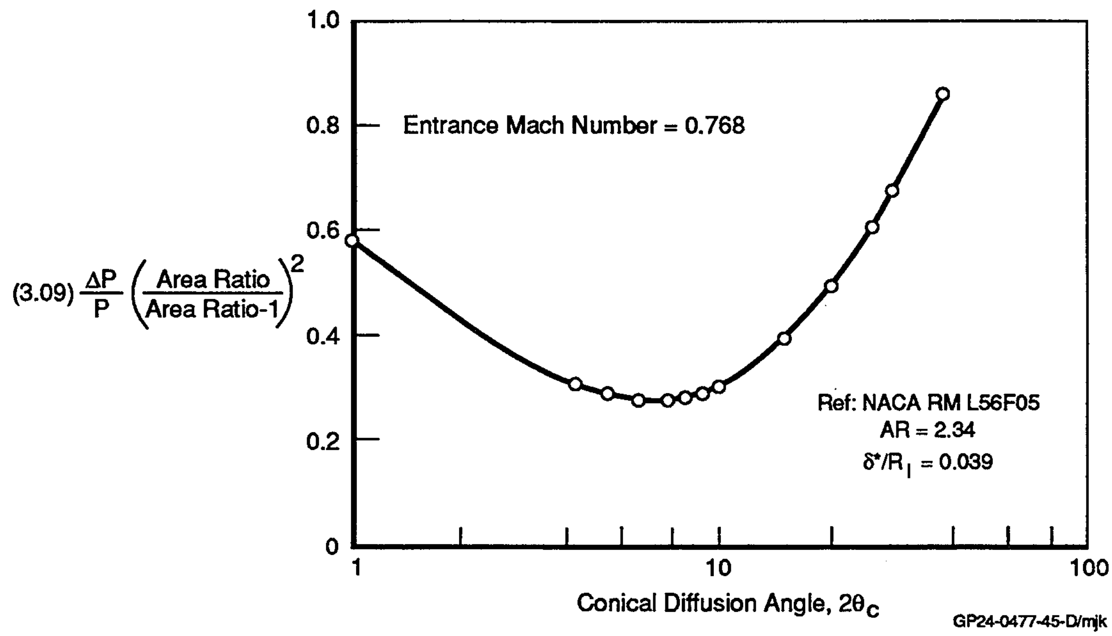


Figure 51. Subsonic Diffuser Loss Correlation

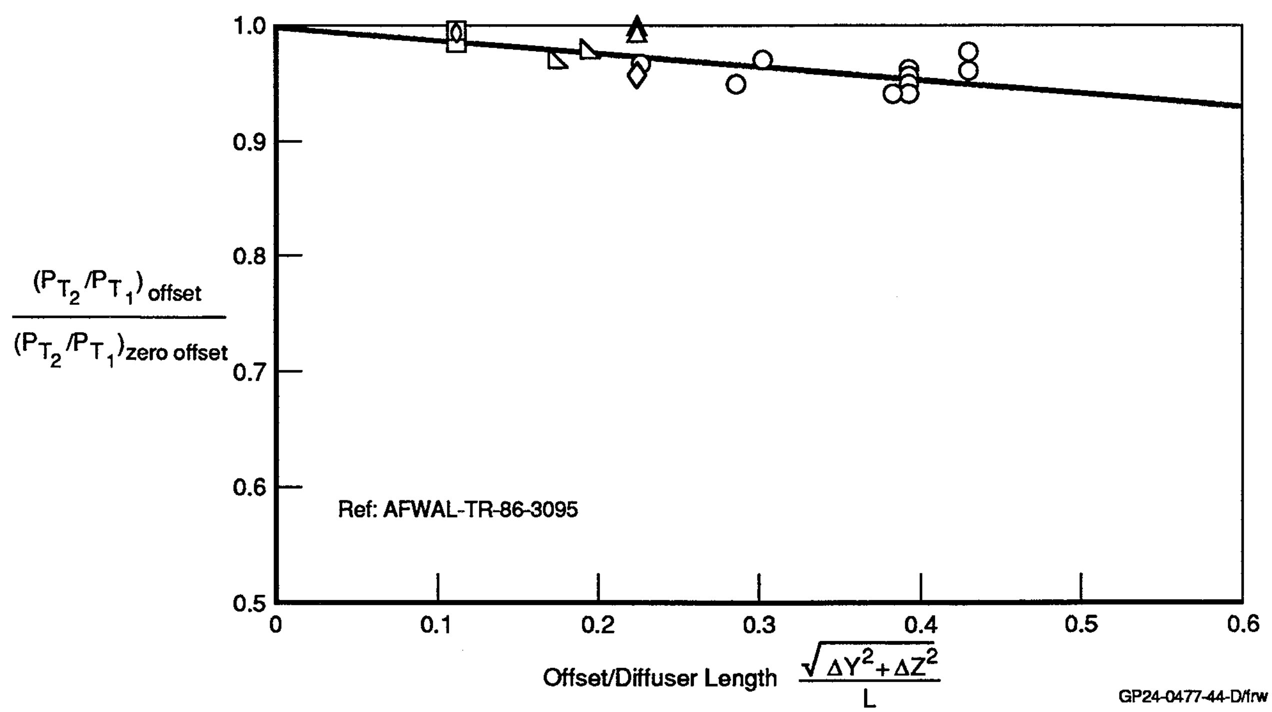


Figure 52. Subsonic Diffuser Offset Loss Correlation

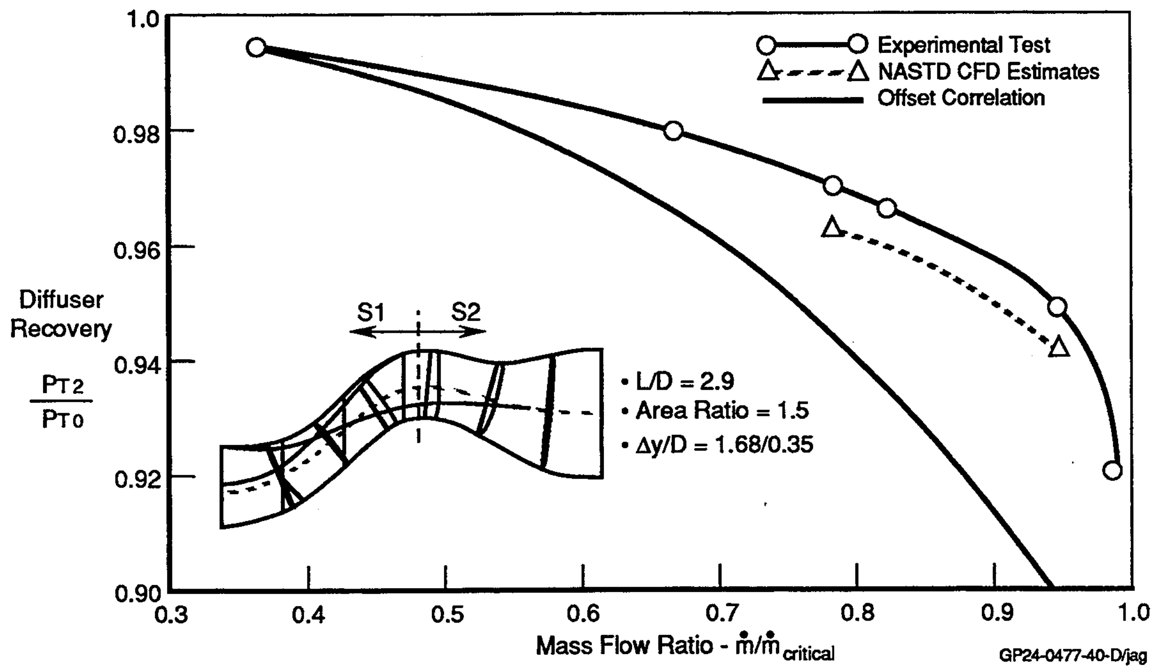


Figure 53. Comparison of CFD-Based, Offset Correlation, and Experimental Test Pressure Recoveries for Serpentine Diffusers

the CFD code providing better fidelity to the experimental results. As a result, the NASTD code was used to analyze the AMA 003 serpentine diffuser, Figure 54. These analyses showed that offset losses can be minimized or eliminated altogether with careful design, and that peak local wall angle may be a better performance predictor than total offset alone. The AMA 002, also analyzed with CFD, with 2-plane offset and large local wall angles is predicted to have the highest losses in the study.

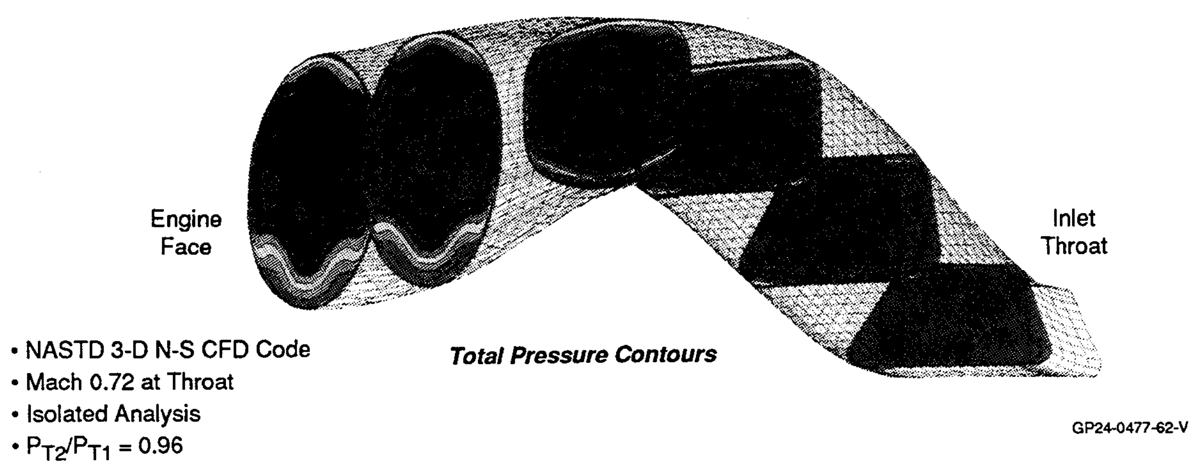


Figure 54. AMA 003 Diffuser CFD Analysis

CFD-based MRF and AMA diffuser recovery characteristics are presented in Figures 55 and 56. In general, the serpentine diffusers pay a 0.2% to 1.5% recovery penalty relative to a conventional diffuser, such as the F/A-18, at design airflow, depending on wall angle. The bifurcated MRF 2001 and 1006 diffusers are predicted to have performance ~1.0 % better total pressure recovery than the F/A-18 due to their relatively short lengths and low offsets. The MRF 1209 serpentine diffuser is predicted to have ~2% more pressure loss than the MRF 2001 diffuser due to 50% more length, and higher offset. The AMA 001 and

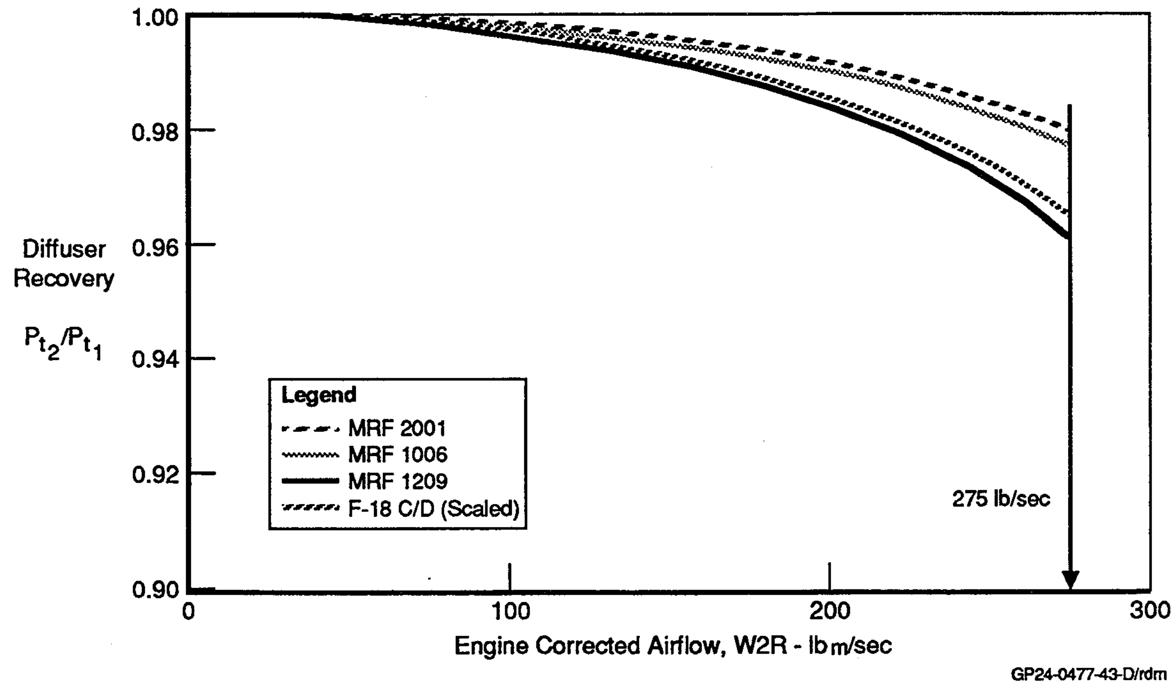


Figure 55. MRF Subsonic Diffuser Recovery Estimates

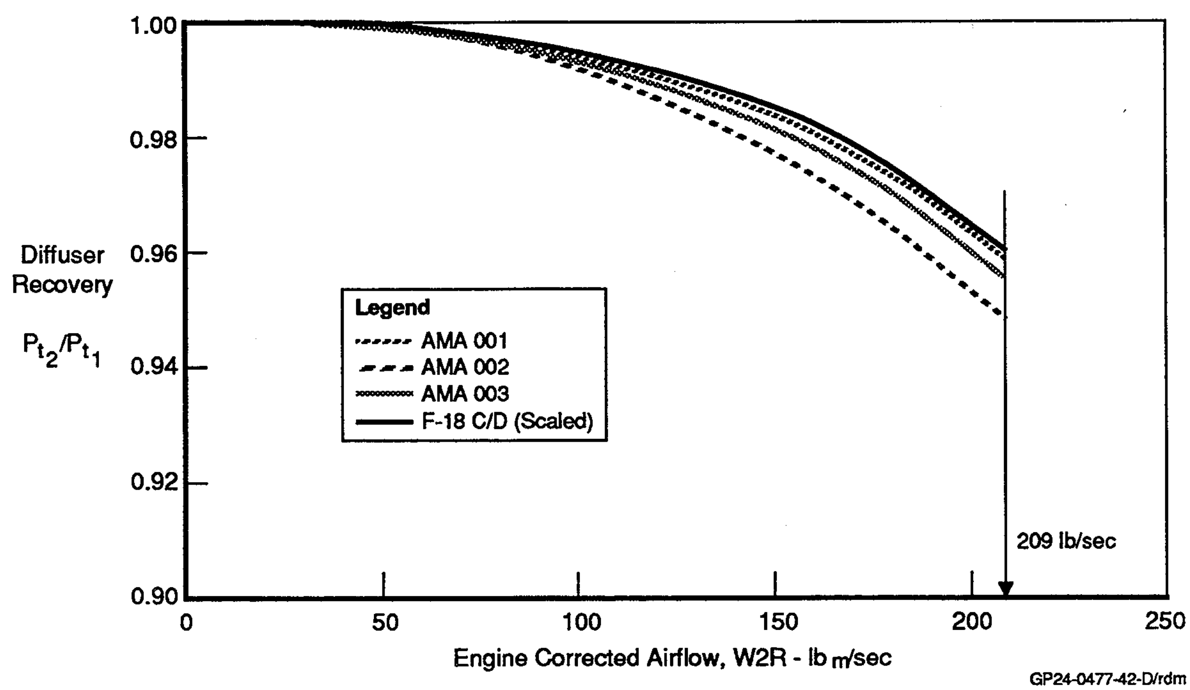


Figure 56. AMA Subsonic Diffuser Recovery Estimates

003 serpentine diffusers have pressure recoveries within ~.5% of the the F/A-18 at design airflow. Th AMA 002 has ~1.0% greater loss than AMA 001 and 003 due to its substantially higher wall angles

MRF and AMA subsonic diffuser cavity returns are a strong function of the diffuser shape, en obscuration, and wall attenuation properties. To assess the diffuser design impact on cavity diffusers developed for this study were analyzed using MCAIR's CAVERN cavity RCS pr Analyses were conducted on CAD-generated duct geometries having metal, RAM an

attenuation properties, and a metal engine face. RCS returns were predicted at azimuths from ±45°, and elevations from ±30°. In general, the serpentine diffusers proved to be superior to single offset diffusers in reducing RCS.

Ducts which allow a direct view of the engine face have "hot spots" that occur in the critical nose sector. RCS attenuation or scattering to the duct walls must occur on the engine face itself to significantly reduce RCS. This can be accomplished using an advanced front frame concept at some cost in pressure ratio, weight and system cost. Engine front frame characteristics are discussed in Section 3.2.4.

Another very important consideration for the subsonic diffuser design is the installed duct weight. Inlet diffusers are the heaviest component of the air induction system, and are a major contributor to overall propulsion system weight. Duct weights are strongly dependent on duct wall structural design and material selection, hammershock pressure loads, and duct geometry. The most important geometric parameter is the duct wetted area. In general fighter and attack aircraft ducts weigh from 2.0 to 2.2 lbs/ft^2 for aluminum construction, and approximately 1.3 lbs/ft^2 for fully co-cured, integrated composite structures. For a 200 ft^2 duct, this amounts to 260 to 440 lbs. of structural weight. Incorporation of multi-layer RAM or RAS materials can increase this weight to over 900 lbs. Diffuser material trades are discussed in more detail in Section 3.2.5.

MRF duct planform and wetted areas are presented in Figure 57. The MRF 2001 bifurcated duct is the lightest, primarily due to its compact size and low entrance aspect ratio. The MRF 1006 duct is the heaviest, primarily due to the bifurcation and relatively high entrance aspect ratio. Incorporation of bifurcation in a cylindrical duct results in a 63% increase in wetted area. Hence, bifurcated ducts must be configured as short as possible to remain low in weight. The MRF 1209 serpentine duct is only 9% heavier than the MRF 2001 duct, despite being 50% longer, and incorporating 100% obscuration.

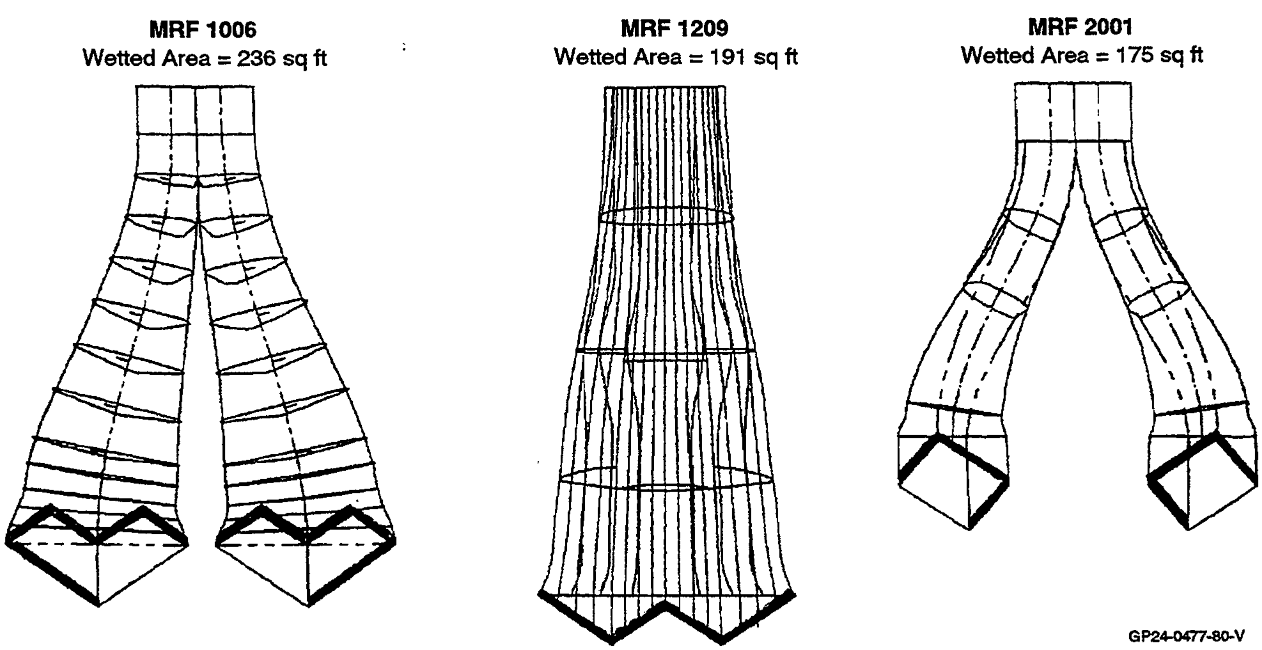


Figure 57. MRF Diffuser Planform and Wetted Area Comparison

The AMA diffuser planforms and wetted areas are illustrated in Figure 58. The AMA 002 diffuser is the shortest and lightest. The AMA 001 duct is heaviest, primarily due to its extreme length, (6.1 L/D). The AMA 003 duct is intermediate, and suffers a 7% wetted area penalty due to the 15% increase in duct area

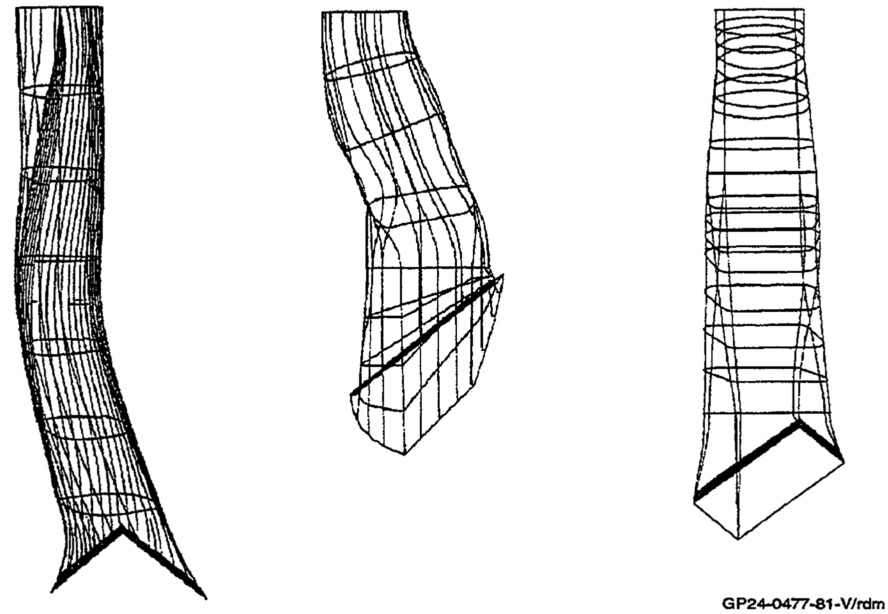


Figure 58. AMA Diffuser Planform and Wetted Area Comparison

incorporated to transport the required secondary airflow to the nozzle. This weight penalty is offset to some extent by the additional weight the AMA 001 and AMA 002 configurations must carry in secondary airflow ducting. These characteristics are discussed in more detail in Section 3.2.6.

3.2.4 Engine Front Frame Configuration Trade Study – As discussed in Section 3.2.3, the inlet cavity design for low RCS return is driven to a large extent by the need to hide the engine face.

An advanced front frame is an engine-mounted or engine integrated radar absorbing device which can hide the engine from direct illumination by radar. Front frame concepts fall into two categories, Waveguide (WG) types and Line-of-Sight (LOS) types. Each type has advantages and disadvantages. WG type frames provide good attenuation over a wide range of azimuths and elevations, and are relatively lighter than LOS frames. LOS frames have pressure losses of 50% to 65% that of WG frames, and are easier to anti-ice, having far fewer ice-collecting edges and corners. Both WG and LOS front frame types can be designed to provide a range of RF attenuations. Subsonic diffusers without 100% obscuration of the engine face benefit the most from front frame incorporation. Parametric front frame RCS investigations were conducted by MCAIR, PW and GE to assess the relative benefit of RAM-coated duct offset vs. front frame incorporation. The results showed that duct offset and front frame incorporation can both reduce cavity signature and work best together. PW's recommendations on front frame configuration for each MRF and AMA configuration are presented in Reference 25 and Figure 59.

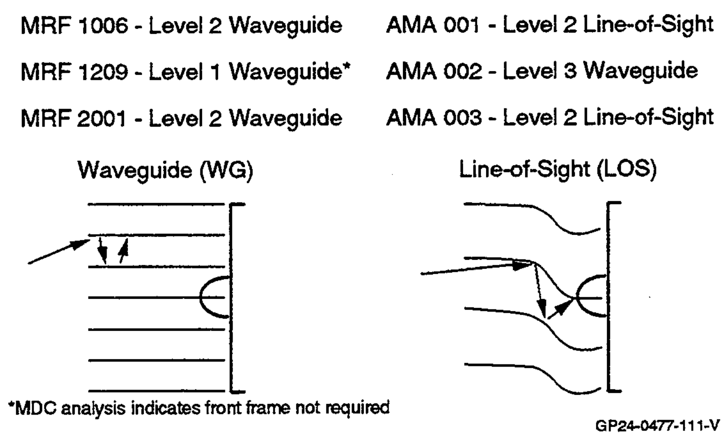


Figure 59. PW Engine Front Frame Integration Recommendations

The incorporation of the front frame pressure loss in the subsonic diffuser pressure recovery can have a substantial impact on performance, Figures 60 and 61. Incorporation of a WG front frame in the MRF 1006 and 2001 brings their respective performance essentially equal to the MRF 1209 serpentine duct. Incorporation of LOS front frames in the AMA 001 and AMA 003 ducts reduces their recoveries. Incorporation of the WG front frame in the AMA 002 duct reduces recovery by 2.3%, and further increases the recovery penalty this concept must pay relative to the longer serpentine concepts.

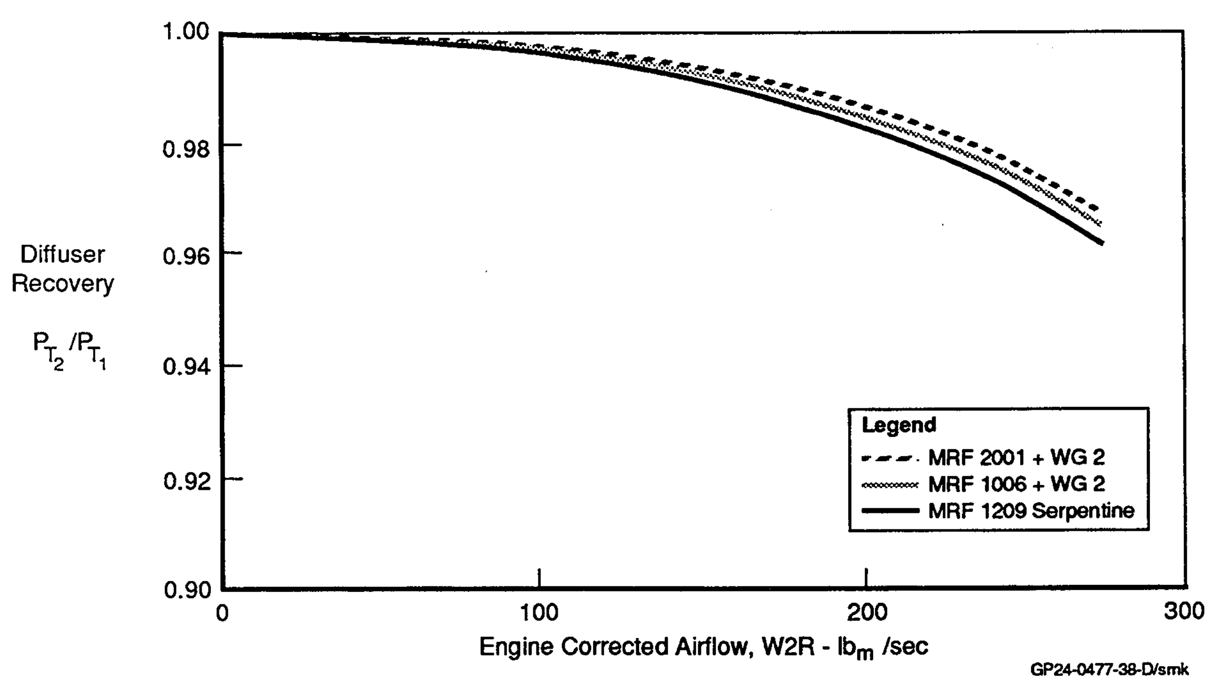


Figure 60. Impact of PW – Recommended Front Frames on MRF Recovery

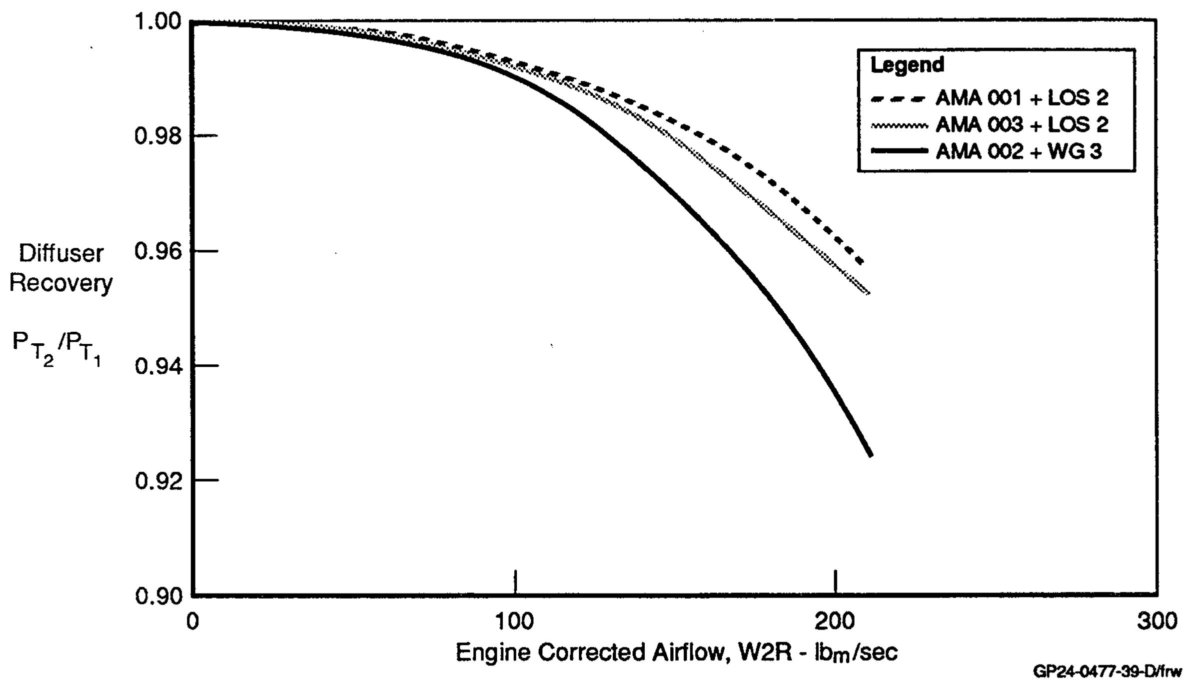


Figure 61. Impact of PW – Recommended Front Frames on AMA Recovery

3.2.5 Inlet Material Selection Trade Study – The selection of material for construction of the air induction system effects the configuration RCS, weight and cost, supportability and structural integrity. The two most important material application areas are the ramp and cowl leading edges, and the subsonic diffuser walls. Both of these areas must be shaped to minimize component RCS scattering while maintaining aerodynamic performance. Shaping alone, however, is insufficient to insure compliance with the nose RCS requirements selected in this study.

The cowl lip shape effects on RCS and aerodynamics were discussed in Section 3.2.2. The material used in the cowl lip does not effect the cowl aerodynamics, but has a major impact on cowl RCS.

The selection of cowl material also affects configuration weight, Figure 62. C-E construction is ~65% of the weight of aluminum construction. Treating C-E within a 35-Mil coating of RAM results in approximately the same total weight, (RAM + C-E structure), as aluminum alone. Use of a multi-layer RAM to achieve better low frequency attenuation can be as much as 100% heavier than aluminum. The weight of these coatings has driven the incentive to look at RAS systems, which weigh ~50% more than aluminum.

The use of RAS edges greatly improves inlet low frequency RCS without dramatically increasing overall inlet system weight. For MRF 1006, which has the longest edge perimeter of all the inlets in the study at ~26 ft., the increment between a RAS edge design, and a 35-mil RAM coated C-E design is less than 39 lbs.

Diffuser wall material selection does not affect diffuser aerodynamic performance, but can have a dramatic impact on cavity RCS, configuration weight, and configuration cost. Duct material weights are compared in Figure 63. As in the case of the cowl edges, aluminum and single-layer RAM-coated CE have about the same weight per square ft. Multi-layer RAM is approximately 130% heavier, precluding its effective use in any practical application. A low frequency-tuned RAS is approximately 65% heavier than aluminum, but far lighter than multi-layer RAM.

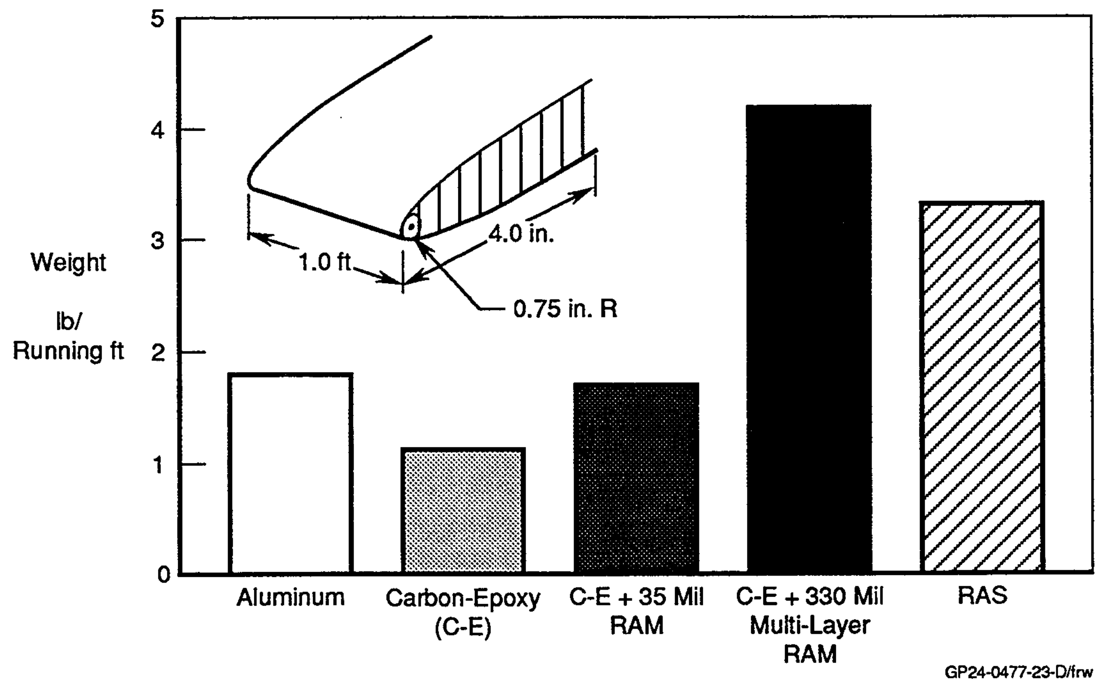


Figure 62. Comparison of Cowl Edge Weights

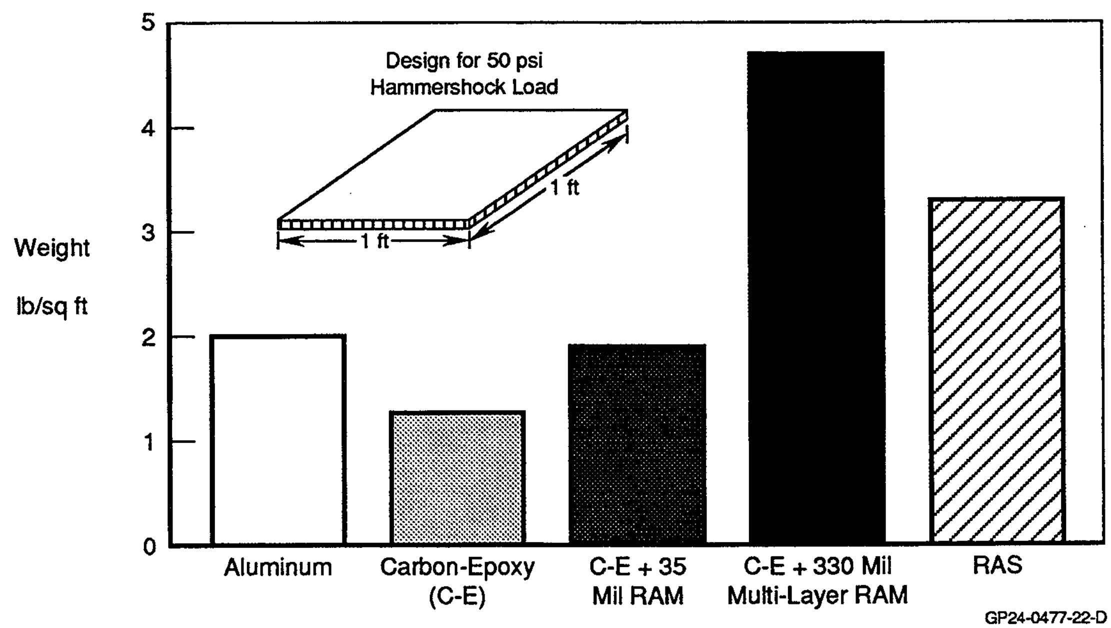


Figure 63. Comparison of Diffuser Wall Weights

The producibility/cost impacts of these materials on air induction system costs were assessed by examining material and manufacturing labor cost estimates from MCAIR prototyping efforts and material and process studies. The relative cost of RAM and RAS duct treatments for representative duct wetted areas and engine face diameters are compared with advanced engine front frame production costs obtained from the engine companies in Figures 64 and 65. In general, the costs for RAM-treated ducts are comparable to advanced front frames costs provided by Pratt and Whitney, Reference 25.

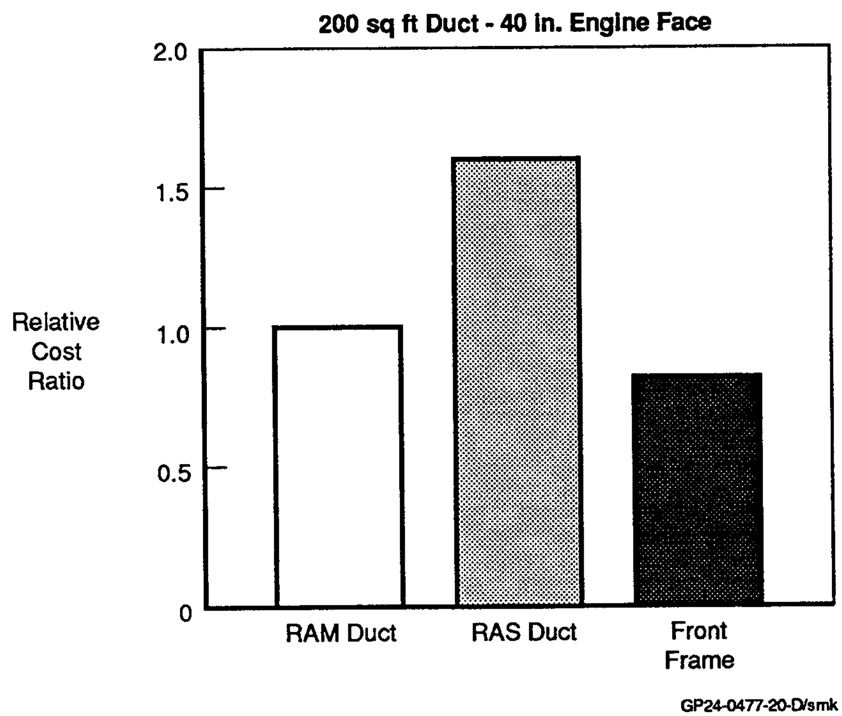


Figure 64. Comparison of Relative MRF Inlet Cavity Treatment Costs

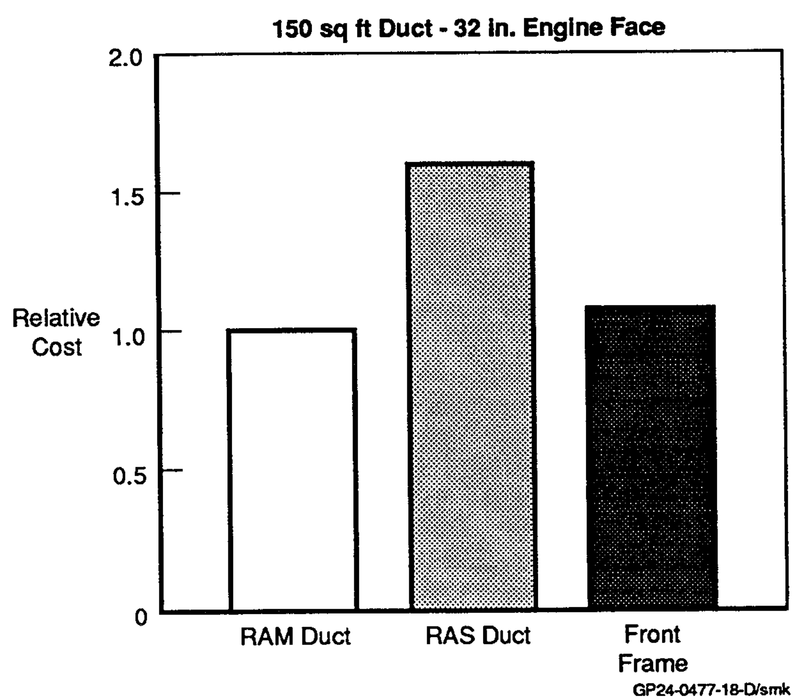


Figure 65. Comparison of Relative AMA Inlet Cavity Treatment Costs

The incorporation of RAS or aggressive front frame technology in a diffuser can be a heavy and expensive proposition. The use of RAS in a 150 sq. ft. duct increases structural weight by 210 lbs. over a RAM-treated duct, while nearly doubling the duct cost. Adding an advanced front frame can add an additional 140 lbs to the system weight, while increasing cost by another 50%. These penalties must be carefully weighed against the RCS benefits each treatment step brings. For a cost-sensitive application like the

MRF, aggressive shaping coupled with RAM-coating on the duct and production front frame probably provides the most cost-effective solution. For an application like the AMA, a RAS duct is probably a requirement. To minimize cost and weight in this application, shaping should be used to minimize the amount of front frame technology required.

3.2.6 Secondary Offtake Configuration Trade Study – The requirement to control exhaust nozzle infrared signature (IR) in many advanced aircraft applications has driven aircraft designers to look for sources of hot part cooling airflow from the air induction system. One potential hot part cooling solution often considered in these studies is to use an ejector nozzle with a ram-air supplied secondary airflow system. This system can take a variety of forms, from entirely separate from the main inlet, to fully integrated. Four potential systems are incorporated in the AMA concepts described in Section 2.3, and illustrated schematically in Figure 66. The AMA 001 system pulls boundary layer air from a 16.6 ft. long forebody through an 16 sq. ft. 50% porosity bleed plate and a 30 ft. long, 15" diameter transport duct to the nozzle secondary plenum. The AMA 002 pulls fuselage boundary layer air off the aircraft dorsal through a 240 in^2 pitot scoop on the aircraft empennage, and into the nozzle secondary plenum. The AMA 003 pulls secondary airflow off the engine face, through an annular transport duct, into a pressurized engine bay, and into the nozzle secondary plenum.

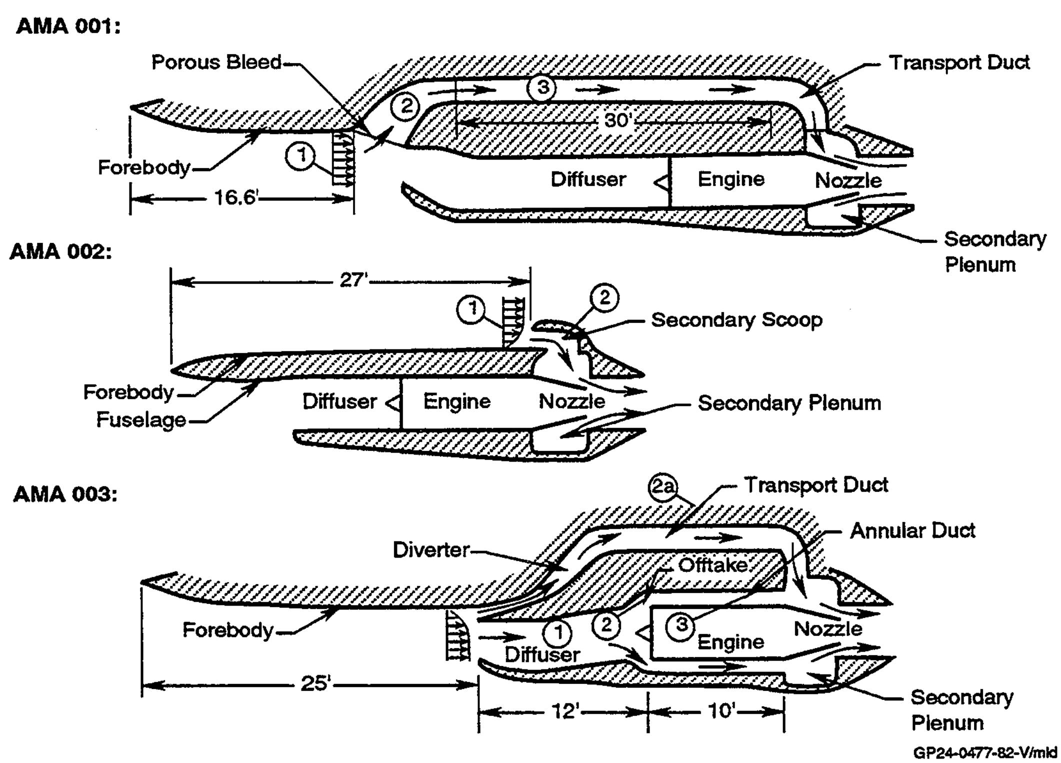


Figure 66. AMA Secondary Airflow System Concept Schematics

Each system was sized to deliver 15% of the engine airflow to the nozzle. Engine company studies reported in Ref. 9, showed that this amount of airflow is required to cool an ejector nozzle shroud to 450°F for survivability.

Delivery of 15% airflow to the nozzle secondary plenum requires secondary flow total pressures significantly greater than ambient. A typical LO ejector nozzle performance and secondary pumping map is illustrated in Figure 67. For a nozzle pressure ratio of 3.0, 15% flow pumping requires a secondary pressure ratio ($P_{Tsecondary}/P_{ambient}$) of 1.5 or greater. At Mach 0.9, an important ingress flight condition for Deep

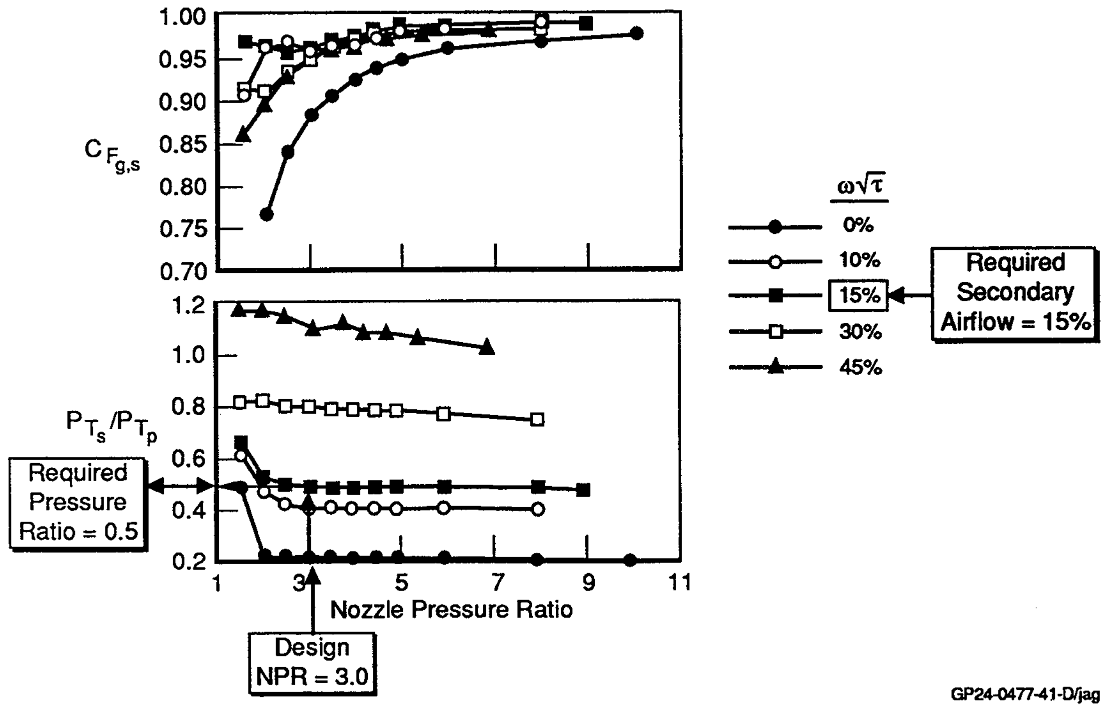


Figure 67. Ejector Nozzle Performance and Pumping Characteristics

Interdiction aircraft, the ram pressure ratio is ~1.7. The secondary airflow system must therefore deliver airflow to the nozzle plenum with pressure losses of no greater than 12%.

Each system was analyzed using data from Refs. 26, 27, 28 and 29 to determine the pressure recovery of the secondary airflow at the nozzle plenum. Results of these analyses are illustrated in Figure 68. The AMA 001 system losses are very large, (over 50%), primarily due to the pressure loss encountered through the large fuselage porous bleed plate. The AMA 002 system has losses over 23%. Over 19% of these losses were due to losses in the 2.5" deep boundary layer, which was completely ingested. Much of this loss can be avoided by incorporating a 2.0 to 3.0" tall boundary layer diverter on the secondary airflow scoop, however the scoop and diverter are both potentially large contributors to the frontal sector RCS, and must be designed and fabricated using the same LO shaping and treatment techniques as the main inlet system. The AMA 003 system had a 9.7% loss in secondary air secondary pressure ratio, and was the only system able to provide sufficient pressure to the nozzle secondary plenum to pump 15% airflow. The largest loss in this system is due to the serpentine diffuser and engine front frame. An alternative AMA 003 system was also analyzed to assess boundary layer diverter exit airflow recovery and avoid the need to oversize the main inlet. Unfortunately, because of the long forebody and short flush diverter incorporated in this configuration, boundary layer diverter losses alone were over 25%, unacceptable for ejector nozzle coding.

This trade study indicated that only two secondary airflow system alternatives deliver enough pressure recovery to provide sufficient ram airflow. These systems are a nozzle ram air scoop on the aircraft empennage with a large enough boundary layer diverter to prevent boundary layer ingestion, and an oversized main inlet which routes airflow around the engine face through annular ducting or the open engine bay, to the nozzle secondary plenum. The first approach, an aft-mounted scoop, is light-weight and simple, but adds a significant RCS contributor to the external moldline and additional aircraft drag. The scoop and diverter must be shaped and treated to achieve configuration nose sector RCS goals, giving up much of the weight advantage of this approach. The second approach requires oversizing of the main inlet and secondary ducting or engine bay pressurization, but does not add to the nose sector RCS. For this reason, the use of a diffuser offtake system is preferable for configurations with aggressive RCS requirements.

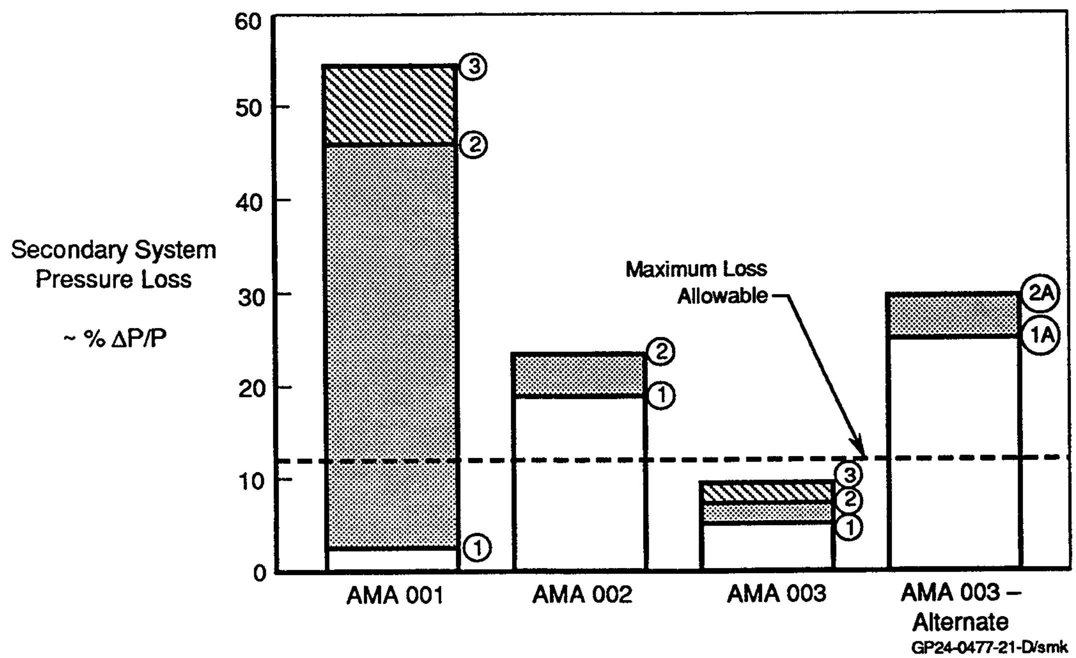


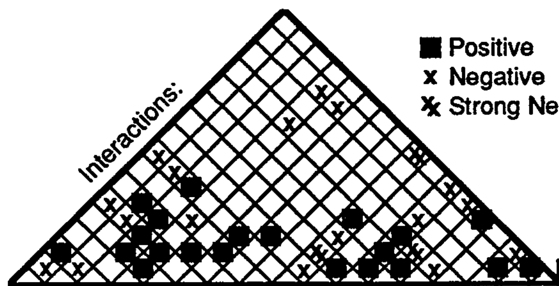
Figure 68. Comparison of Total Pressure Losses – Secondary Airflow Systems

3.3 CONFIGURATION SELECTION

The selection of the "best" air induction configuration is a difficult process because of the large number of factors involved, and the impact of the inlet configuration on the rest of the weapon system. Most of the important qualities of the air induction system are listed in the Quality Function Deployment (QFD) matrix developed in Task II, and illustrated in Figure 69. The results of the detailed trade studies discussed in Section 3.2 were used to assess and then rank each configuration air induction system "quality" listed in the QFD matrix.

The most important MRF inlet qualities are the inlet RCS; the inlet post-stall, transonic maneuvering, and supersonic performance, inlet supersonic drag; inlet weight; inlet supportability; inlet growth potential; and inlet cost/producibility. Most of these qualities can be assessed quantitatively, however many qualities, such as inlet supportability or inlet growth potential, are somewhat subjective and difficult to assess. For this study, these non-quantitative qualities were considered to be equal for all configurations, and did not effect the relative rankings.

MRF forebody/inlet aperture and inlet cavity RCS characteristics are summarized in Figure 70. The MRF 1006 and 2001 are limited by their cavity performance.



■ Positive
x Negative
✱ Strong Negative

Relationships:
None 0
Weak 1
Moderate 3
Strong 5

What's: / How's:	Forebody Shape	Forebody BLM	Inlet Ext. Diffuser	Inlet Lip Config.	Inlet Contraction	Inlet Location	Inlet BLM	Aux. Inlet Config.	Diffuser Bifur.	Diffuser BLM	Diffuser Obscuration	Diffuser Vane Config.	Engine Front Frame	Anti-Ice Tech.	Secondary Offtake	Cowl/Ramp Lip RAS	Diffuser Wall RAS	Why's: AMA System Weighting	MRF System Weighting
Airframe Signature - Radar Cross Section	3	3	3	3	0	3	3	0	3	0	5	5	5	0	3	5	5	10	7
Airframe Signature - Infrared	0	0	0	0	0	0	0	0	0	0	1	1	1	0	5	0	0	8	0
Int. Performance - Static (Takeoff/Landing)	1	1	1	5	5	1	0	5	3	3	3	3	3	0	0	0	0	10	1
Int. Performance - Post-Stall (M=0.3)	3	1	1	5	5	5	0	5	1	3	3	3	3	0	0	0	0	0	7
Int. Performance - Trans. Maneuver (M=0.9)	5	3	1	3	3	5	1	5	3	3	3	3	3	0	0	0	0	5	8
Int. Performance - Supersonic Cruise	5	5	5	3	3	5	5	1	1	3	3	3	3	0	0	0	0	0	6
Inlet Drag - Subsonic Cruise	1	1	3	3	3	1	1	0	0	0	0	0	0	0	1	1	1	3	3
Inlet Drag - Supersonic Dash	1	3	5	5	5	3	3	0	0	0	0	0	0	0	1	1	1	0	5
Inlet Icing Performance	0	0	1	5	0	0	0	0	0	0	0	5	5	5	3	5	1	8	1
Inlet System Weight	0	1	3	1	1	1	3	3	5	1	5	3	3	1	3	3	5	9	9
Inlet Airflow Growth Potential	1	0	3	5	5	1	0	0	5	0	3	0	0	0	3	0	0	6	6
Inlet Supportability	0	3	0	1	0	1	3	1	0	3	0	3	3	3	1	5	5	5	8
Inlet Productivity and Cost	0	3	3	3	0	0	3	3	3	3	5	3	5	3	3	3	5	5	10

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Figure 69. MRF and AMA Air Induction System Quality Function Deployment Matrix

- Untreated Metal Fuselages Roughly Equivalent in RCS
- Parasitic Treatments Will Bring Metal Fuselages Within Budget
- MRF 1209 Serpentine Duct With Parasitic Treatment Equivalent to MRF 1006 and MRF 2001 With Parasitic Treatment and Waveguide Front Frames at High Frequencies
- MRF 1209 Serpentine Duct Has Better Performance at Low Frequencies
- Overall MRF 1209 Has Lowest Integrated Signature

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Figure 70. MRF Radar Cross Section Comparison

MRF inlet performance and drag effects on installed thrust, (thrust minus throttle-dependent drags) are summarized for three important flight conditions in Figure 71. The MRF 1209 has marginally better post-stall and transonic performance than the other concepts primarily due to better cowl lip flowfield shielding at angle-of-attack, Figure 48. MRF 1006 has substantially better supersonic cruise and dash performance than the other concepts due to incorporation of the caret external diffusers.

MRF air induction system weights are compared in Figure 72. MRF 1209 has the lowest overall weight, primarily due to omission of the engine front frame. MRF 2001 has the lowest diffuser wetted area and diffuser weight. Inlet relative costs are summarized in Figure 73. Again, because of the omission of the engine front frame, the MRF 1209 has substantially lower cost than the other concepts.

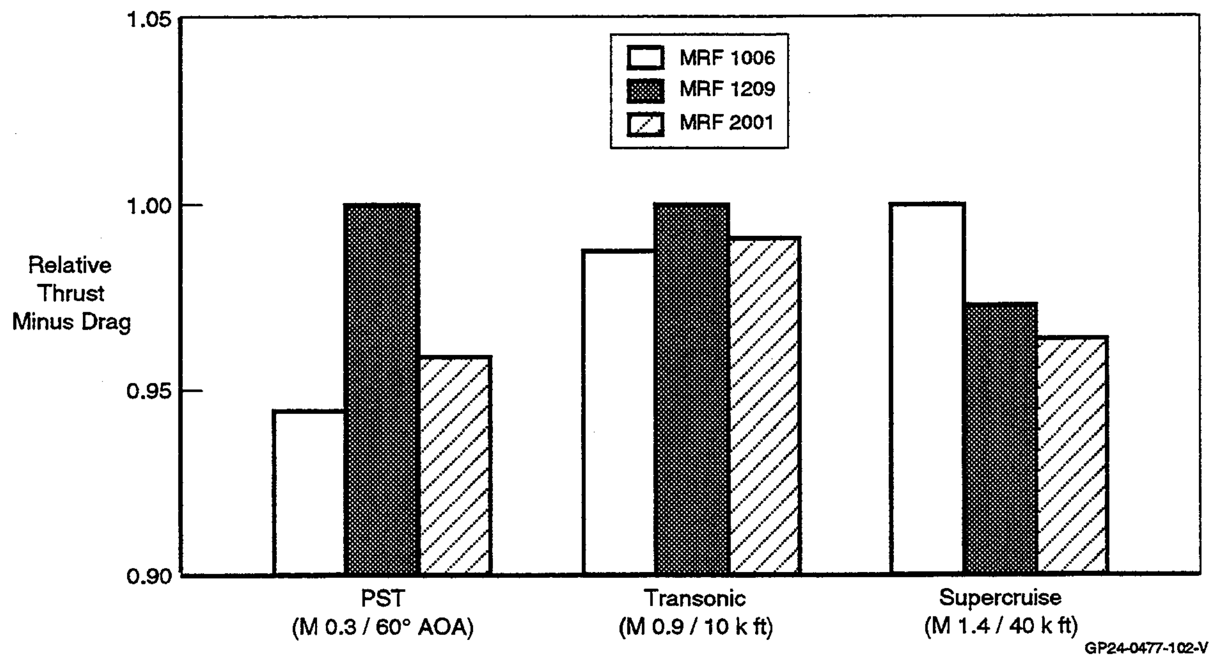

Figure 71. Comparison of MRF Inlet Recovery and Drag Effects on Thrust

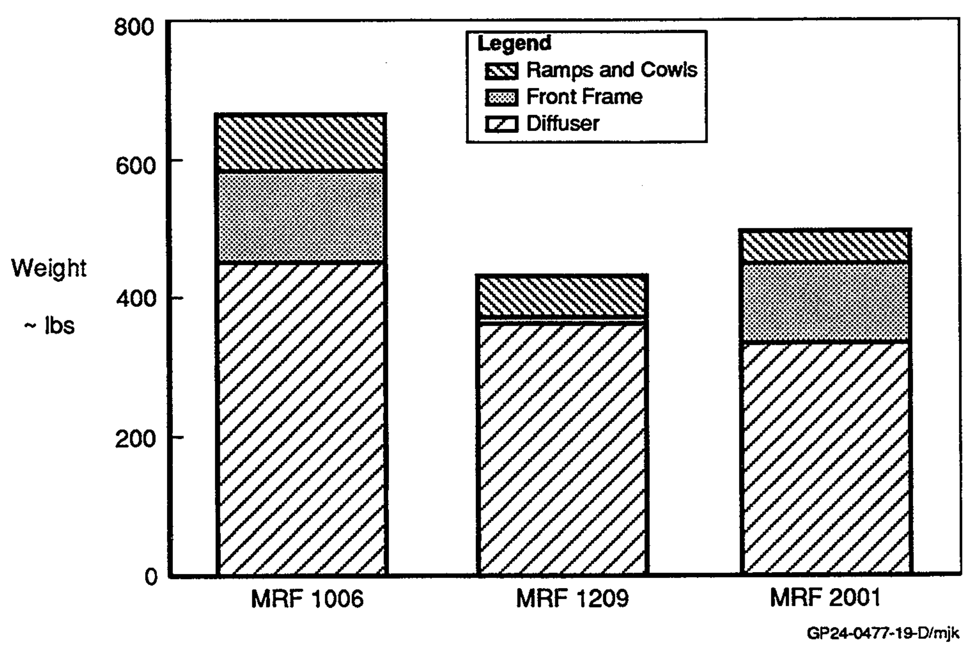

Figure 72. Comparison of MRF Inlet Weights

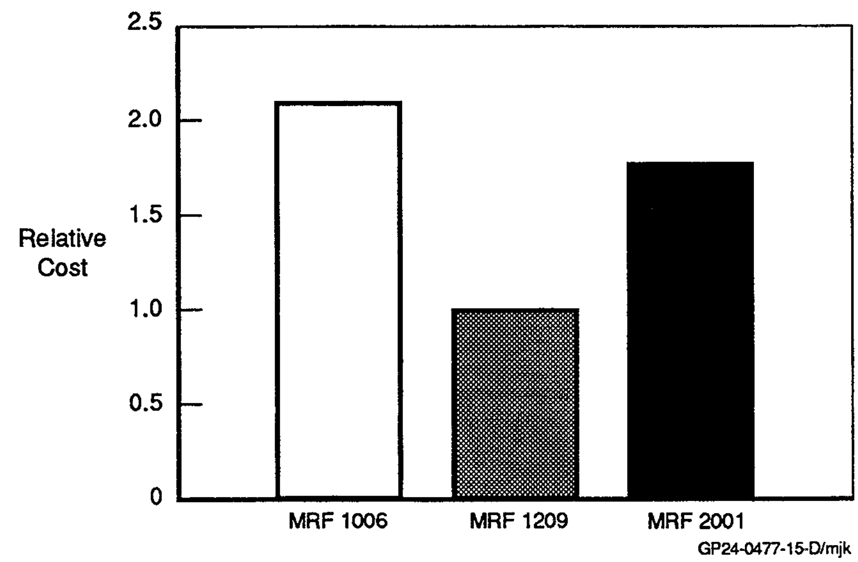

Figure 73. Comparison of MRF Inlet Relative Costs

The MRF concepts were ranked based on the QFD matrix MRF weightings assigned to each "quality" by MCAIR's propulsion integration experts. Five points were assigned to first place, three to second place, and one to third place in each quality category. Total QFD scores were then calculated by multiplying the assigned points by the appropriate weighting factor and summing. The MRF 1209 was the overall winner due to superior RCS, maneuvering performance, lower weight and lower cost, Figure 74. To compare these results for a more traditional figure-of-merit, Takeoff Gross Weight (TOGW), the installed thrust, drag and weight differences assessed between the concepts were used to determine relative aircraft gross weight increments using sensitivities developed for the USAF/WL Propulsion Integration for Aerocontrol Nozzles (PIANO) program, Reference 10, and MCAIR's advanced fighter design studies. These assessments showed that the MRF 1209 configuration had the lowest TOGW, all non-inlet factors being equal, Figure 75. The MRF 1006 and 2001 configurations had roughly comparable TOGW's.

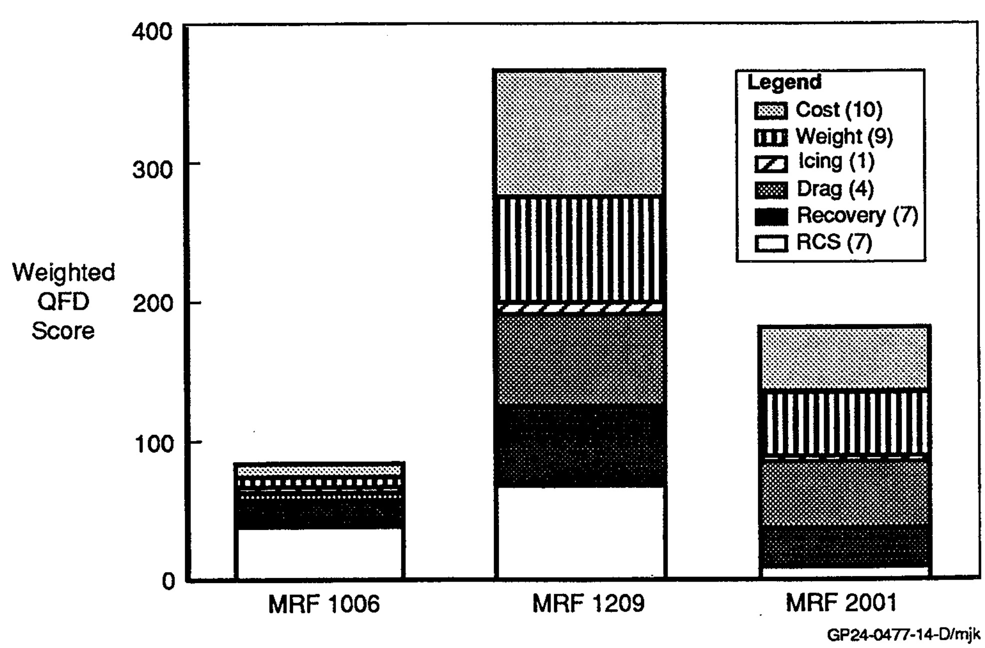

Figure 74. QFD Ranking of MRF Inlet Concepts

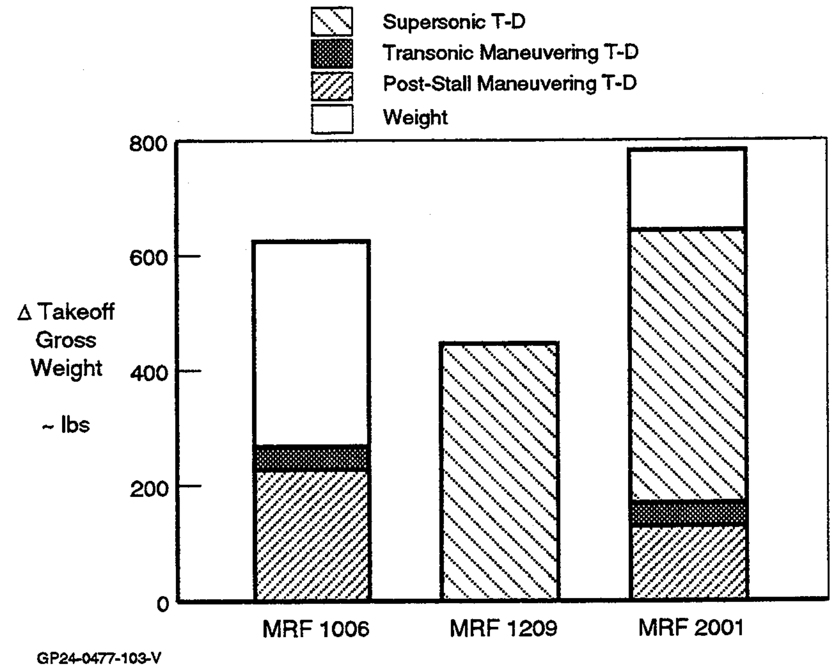

Figure 75. TOGW Ranking of MRF Concepts

The most important AMA inlet qualities are the inlet RCS; the system IR signature; the inlet static (take-off/landing) and transonic cruise performance; inlet icing performance, inlet weight, inlet supportability; and inlet cost.

AMA forebody/inlet aperture and inlet cavity RCS characteristics are summarized in Figure 76. The AMA 001 and 003 are approximately equal, and better than the AMA 002. This configuration has marginally higher frontal sector RCS, primarily due to the lack of diffuser RCS performance.

- AMA 001 and 003 Untreated Metal Fuselages Roughly Equivalent in RCS
- AMA 002, Untreated Fuselage (Flying Wing) Better at Low Frequency
- Integrated Absorbers (Edges, etc) Will Bring All Metal Fuselage Within Budget
- AMA 001 and AMA 003 Serpentine Ducts With Integrated Absorbers and Hiding Front Frames Within Budget
- AMA 002, With Waveguide Front Frame Has "Hot Spots" Off Nose-On, Limited Low Frequency Performance
- Overall AMA 001 and 003 Have Lowest Integrated Signature

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Figure 76. AMA Radar Cross Section Comparison

AMA inlet performance and drag effects on installed thrust are compared in Figure 77. The AMA 001 and AMA 003 have essentially the same performance at both Single Engine Rate-of-Climb (SEROC) and transonic conditions. The AMA 002 suffers a 5% thrust penalty at SEROC, and 3% at transonic cruise due to slightly higher diffuser recovery losses, and significantly higher front frame losses.

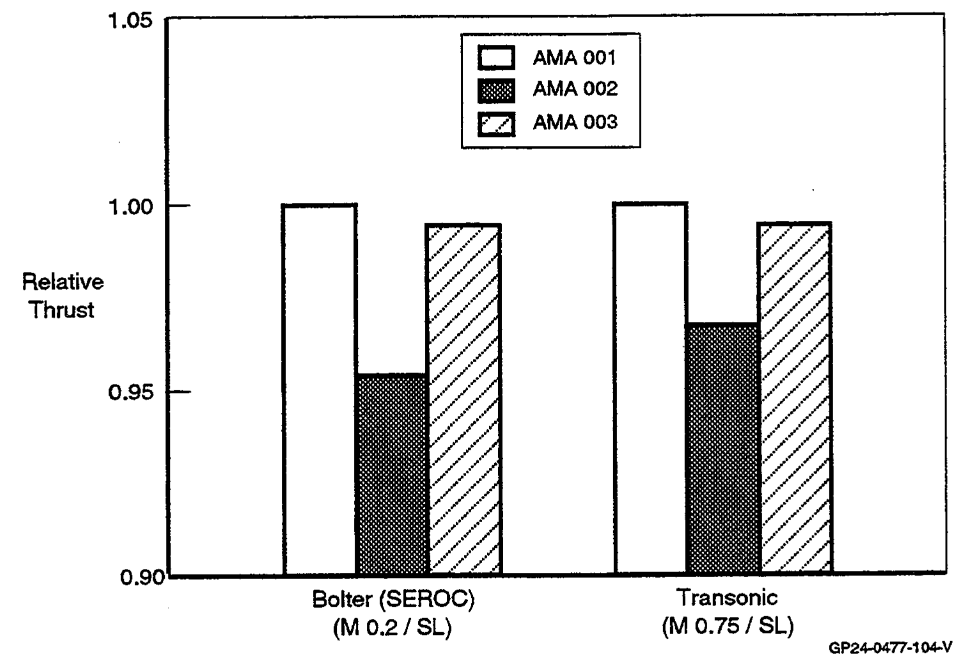


Figure 77. Comparison of AMA Inlet Recovery and Drag Effects on Thrust

AMA air induction system weights are compared in Figure 78. The AMA 002 has the lightest overall weight, despite the incorporation of the heaviest front frame configuration. This is due to the overwhelming weight impact of the RAS diffuser weights. The AMA 003 is the second lightest because of its incorporation of an intermediate length duct and LOS II front frame. AMA air induction system relative costs are compared to each other and to the MRF 1209 configuration in Figure 79. AMA costs are all roughly comparable, with the AMA 002 having slightly lower costs due to reduced diffuser RAS requirements.

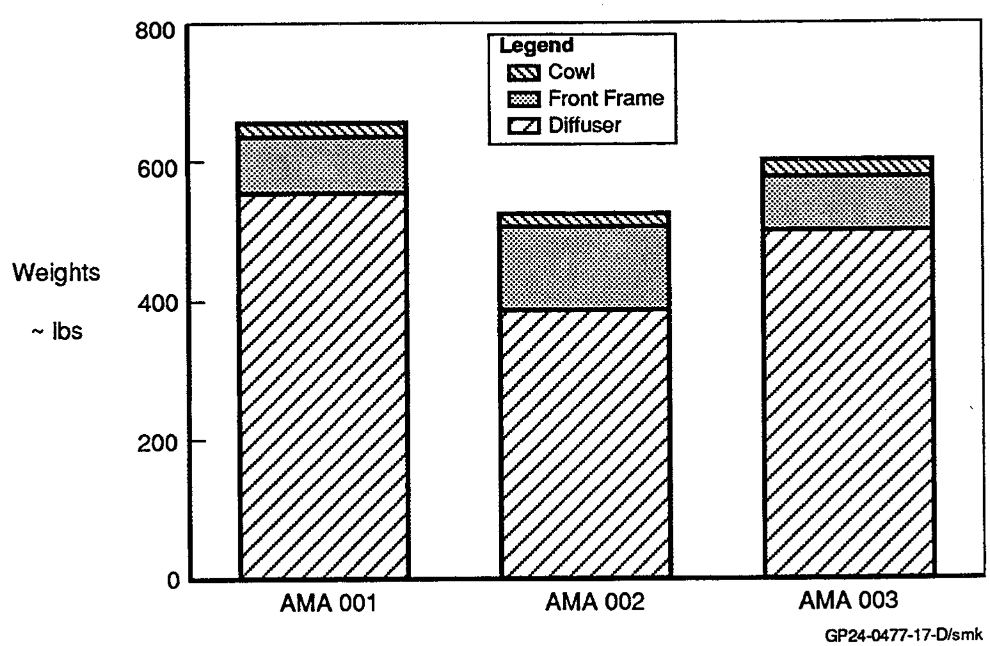


Figure 78. Comparison of AMA Inlet Weights

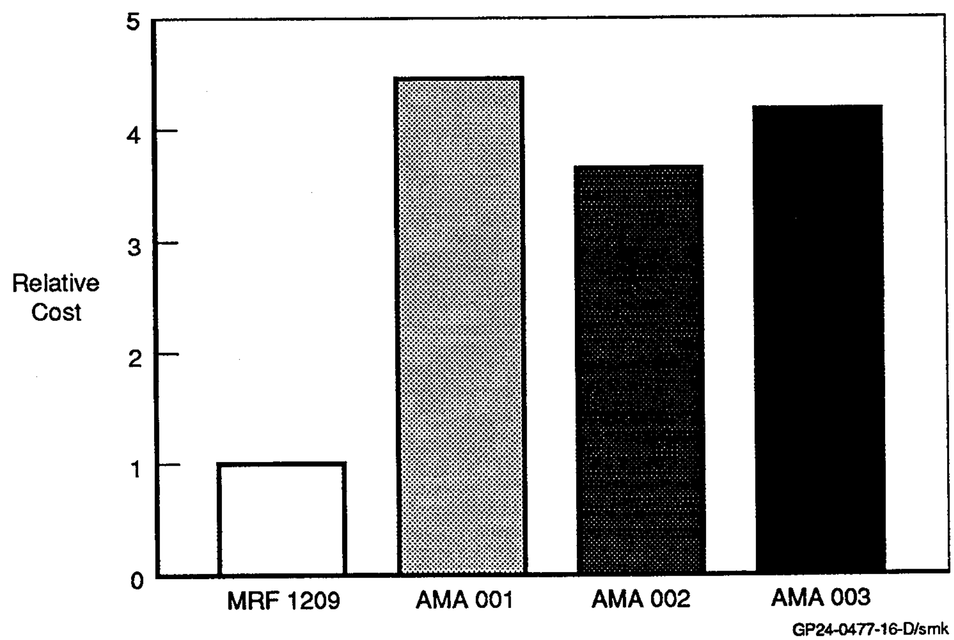


Figure 79. Comparison of AMA Inlet Shipset Relative Costs

The AMA concepts were ranked based on AMA weightings assigned by MCAIR's propulsion integration experts, in the same manner as the MRF concepts. The AMA 003 concept had the highest scores, Figure 80, primarily due to superior secondary airflow system performance (IR signature), lowest cost, and a balance between performance, drag and radar cross section. The AMA 001 had marginally lower scores primarily due to shortcomings in cost, weight, and secondary airflow system performance. TOGW impacts of the installed thrust, drag and weight differences were also assessed in the same manner as the MRF configurations, Figure 81. All configurations were comparable in TOGW. AMA 001 and 003 advantages in recovery and drag were largely offset by AMA 002's advantage in lighter weight.

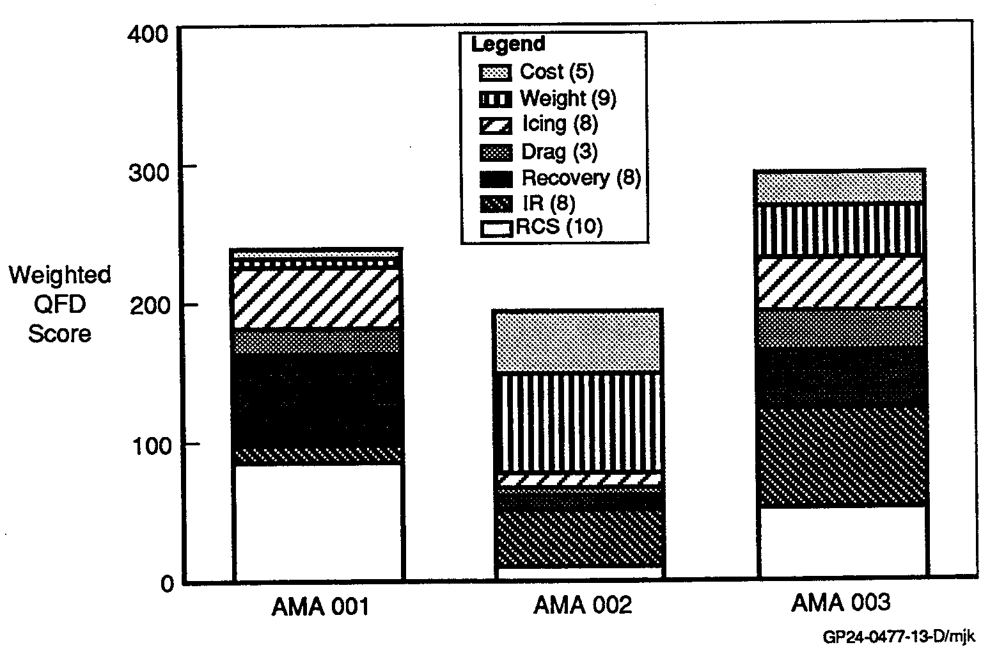


Figure 80. QFD Ranking of AMA Inlet Concepts

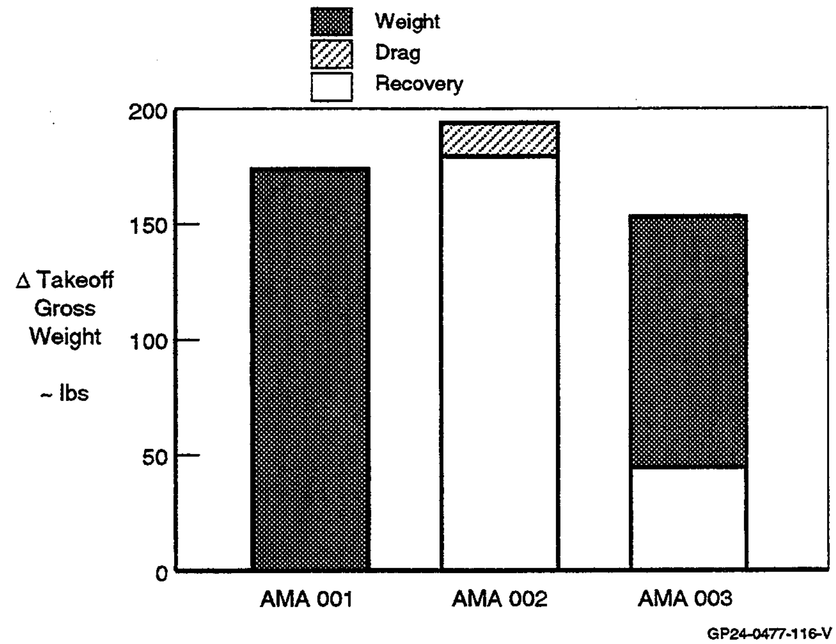


Figure 81. TOGW Ranking of AMA Concepts

4.0 TASK III – RESEARCH PROGRAMS

In Task III, we assessed database deficiencies which added uncertainty to the conceptual design and trade studies completed in Tasks I and II. We then analyzed these deficiencies to develop a prioritized list of aerodynamic and low observable research topics which would benefit from generic engineering investigations.

Technology “roadmaps” to guide follow-on engineering investigations were assembled using projected program development schedules from MCAIR system engineering studies. These technology development plans include inlet aerodynamic development, low observable integration development and engine front frame development. From these roadmaps, wind tunnel test plans, and were developed including test parametrics and test. A complete nosetip-to-engine-face computational fluid dynamic analysis at the design flight condition was completed for MRF 1209 and AMA 003 configurations, using MDC's NASTD 3-D Navier-Stokes CFD code.

Two conceptual wind tunnel models were designed to be compatible with existing NASA wind tunnels, using existing engine face rake and mass flow plug hardware, and to meet the test objectives and be compatible with sting support systems, Reference 30. These designs were based on the QFD-selected configurations analyzed with CFD, and include parametrics in the forebody and inlet boundary layer management, inlet cowl lip, inlet subsonic diffuser, and engine front frame geometries. The Task III study flowchart is illustrated in Figure 82.

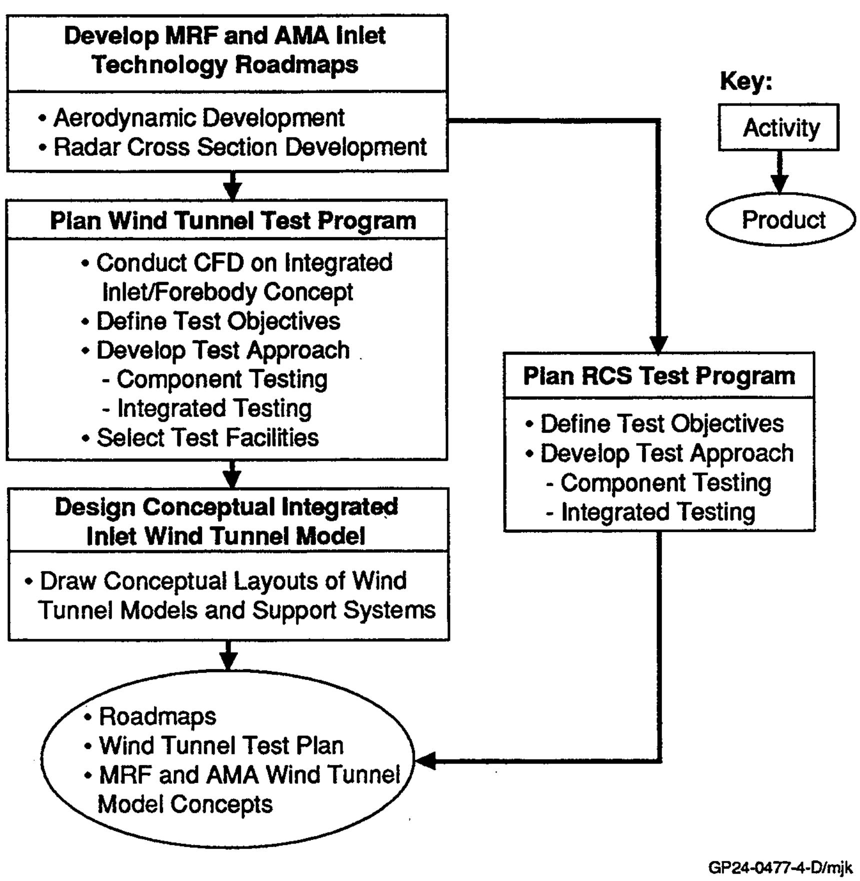


Figure 82. Task III - Research Programs

4.1 DATABASE DEFICIENCIES

Low risk, high confidence conceptual design of LO air induction systems depends, fundamentally, on flexible fluid dynamic and electromagnetic analysis tools which are validated using high quality, relevant experimental data, and on a broad, parametric design database. A very complete database has been developed for conventional, non-LO fighter and attack inlet configurations through over 30 years of aerodynamic research and development. This database has been effectively used to develop the current generation of fighter and attack aircraft, including the A-6, F-15, F-16 and F-18. Application of this database to LO fighters and attack aircraft has been problematic, however, because of the lack of data available on the impact of LO design features, such as chines, faceting, cowl sweep and diffuser obscuration (offset/vanes/front frames/etc.).

This lack of database, coupled with the immaturity of propulsion computational fluid dynamic analysis codes, lead to increased development risk and cost in the B-2, A-12, YF 22 and YF-23. Every one of these developments had to create a new aerodynamic and RCS technology set to allow definition of the propulsion flowpath moldlines for detail design, fabrication, and flight test. Each of these technology sets was developed to better understand each respective set of configuration – specific features and integration concepts. Each dataset is quite detailed, but also quite "narrow", due to the highly focused nature of aircraft development work. The inability, (for security and proprietary rights reasons), to merge and "parametricize" these technology sets hinders the development of next generation systems such as the MRF and AMA.

The development of a truly parametric, non-configuration specific LO air induction system database has been undertaken by the USAF, USN, NASA, MCAIR, and other military aircraft contractors, Figure 83 only in the past five years. The initial "entries" to this database are, for the most part, on a component basis. MCAIR has done a large number of studies on the aerodynamic and LO integration of LO external diffusers and serrated cowl lips, serpentine subsonic diffusers, and LO forebody flowfield effects, but little in the way of generic, (non-program specific), integrated inlet analysis, and aerodynamic and performance testing,

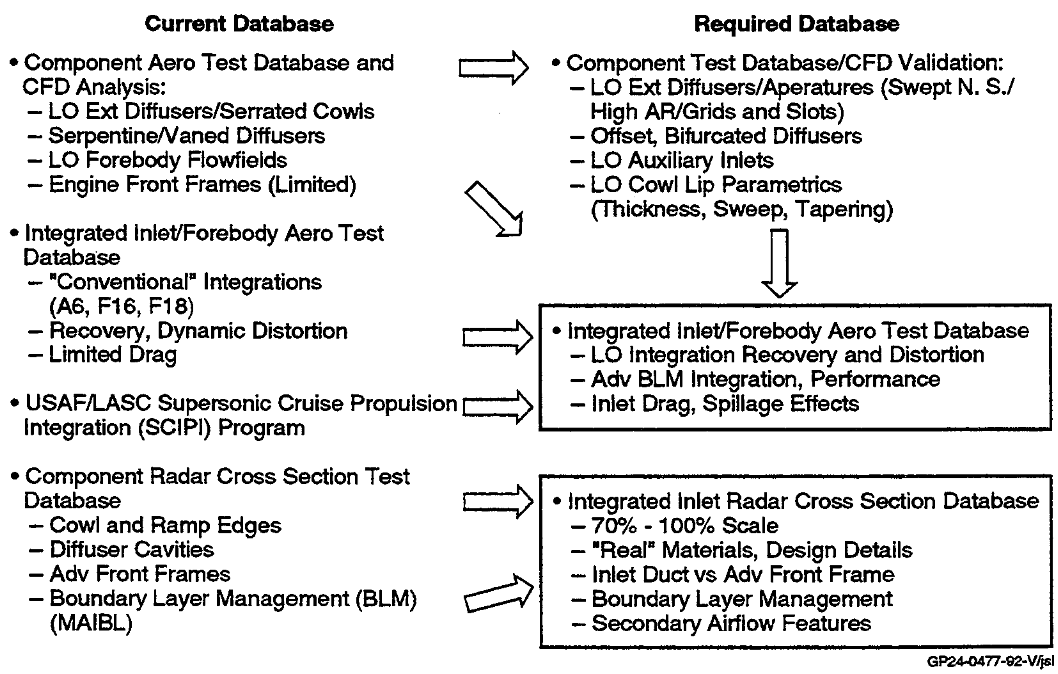


Figure 83. LO Air Induction System Conceptual Design Database Deficiencies

References 31, 32, 33, 34. The USAF Wright R&D Center Flight Dynamics Laboratory and Lockheed Aerodynamic Systems Co. have developed an LO inlet integration database under the Supersonic Cruise Propulsion Integration (SCIPI) program for LO, twin-engine supercruise fighters, Reference 35. This program has been a valuable addition to the LO propulsion integration database but is limited in the scope of configuration parametrics examined, and is insufficient to guide configuration synthesis of single-engine fighters or attack aircraft at lower signature levels.

The inlet generic design database is also particularly limited in propulsion component/integration radar cross section analysis and test data. No generic, available, experimental database yet exists to confirm code predictions for configurations of this type. In addition, configuration RCS analysis is particularly hindered by the lack of similarity laws or parameters to permit reliable scaling of shaping or material EM characteristics.

New generic experimental and analytical databases are required to fill the LO air induction system design database voids previously cited. The most pressing areas of need are highlighted in Figure 83, and center on experimental tests and analysis of complete, integrated systems. While sufficient data exists on individual inlet components to support the conceptual design trades discussed in Section 3.0, no generic data exists to determine how all these features will work together from either an aerodynamic performance or RCS standpoint. For this reason, the most important contribution NASA researchers can make to LO propulsion system integration is the application of NASA's wind tunnel and microwave test facilities and analytical codes to the study of inlet component **integration** on system aerodynamic performance and RCS. Two areas where the database needs particular attention are the areas of inlet/airframe aerodynamic integration and inlet duct/front frame signature integration, with particular emphasis on wall material treatments. Both of these areas need to be addressed in parametric experimental investigations using high quality facilities, test articles and instrumentation.

Integration parametrics should consider as large a set of generic, high value configurations as practical, using a "case study" approach. Such a case study approach would begin with a conceptual design study to define requirements, configurations and important design trades, followed by simple inlet component tests and/or analyses to define isolated component aerodynamic performance and RCS, which are, in turn, followed by large-scale integrated tests to determine how the aerodynamic performance and RCS characteristics change due to interactions with other design features.

For fighter concepts like the MRF, important design features with potential interactions include the inlet/forebody integration, the inlet cowl lip shape and planform, the forebody and inlet boundary layer management systems, the subsonic diffuser, the engine front frame and any auxiliary inlets. For attack aircraft concepts like the AMA, important design features include the same components as the MRF, with the addition of the secondary airflow system. LO integration studies, for both concepts, must consider these features as well as additional design features such as the material and structural concepts. Each "case study" would examine the interactions of all these features using analysis or parametric testing with modular model concepts. Multiple case studies could then be employed to develop the broadly applicable database necessary to fully validate CFD and RCS design codes and provide for low risk LO propulsion system integration.

4.2 TECHNOLOGY ROADMAPS

The development of technologies to support design of next generation fighter and attack aircraft propulsion systems must be planned in the context of the timeframes currently anticipated for fielding these weapon systems. Modern aircraft development programs require very long lead times from conception to Initial Operating Capability (IOC). The YF-17/F-18 C/D program received go-ahead more than 27 months before prototype first flight, 80 months before aircraft first flight and 120 months (10 years) before IOC! These long development times require that technology concepts which shape the aircraft moldline must

be matured, literally, years before the planned IOC. For technology development planning purposes, the aircraft development histories depicted in Figure 84 were analyzed to assemble the generic military aircraft development schedule shown in Figure 85. As per the 1986 Packard Commission defense system development guidelines, this schedule includes a “paper” concept exploration stage, a “mission-capable” demonstrator prototype stage, an engineering/manufacturing development stage, and a production stage. Propulsion system technology freeze dates occur at Milestone 1, the beginning of the demonstration/validation stage, for prototype moldline concepts, and 12 months prior to Milestone 2, the beginning of the Engineering and Manufacturing Development (EMD) phase, for all weapon system moldline, RCS integration, material and avionic (control) technologies. These freeze dates occur well before IOC, on the order of 102 months, (8 1/2 years), and 66 months, (5 1/2 years), respectively.

Using this generic development schedule, recommended technology roadmaps for MRF and AMA propulsion integration development are presented in Figures 86, 87, 88 and 89 using the most up-to-date IOC dates postulated for these aircraft, Reference 5. These technology roadmaps highlight the test database development dates usable to configuration designers for these efforts. Using an IOC of 2005 for AMA and 2010 for the MRF, it appears that the most near-term technology database need is for the AMA prototype moldline definition.

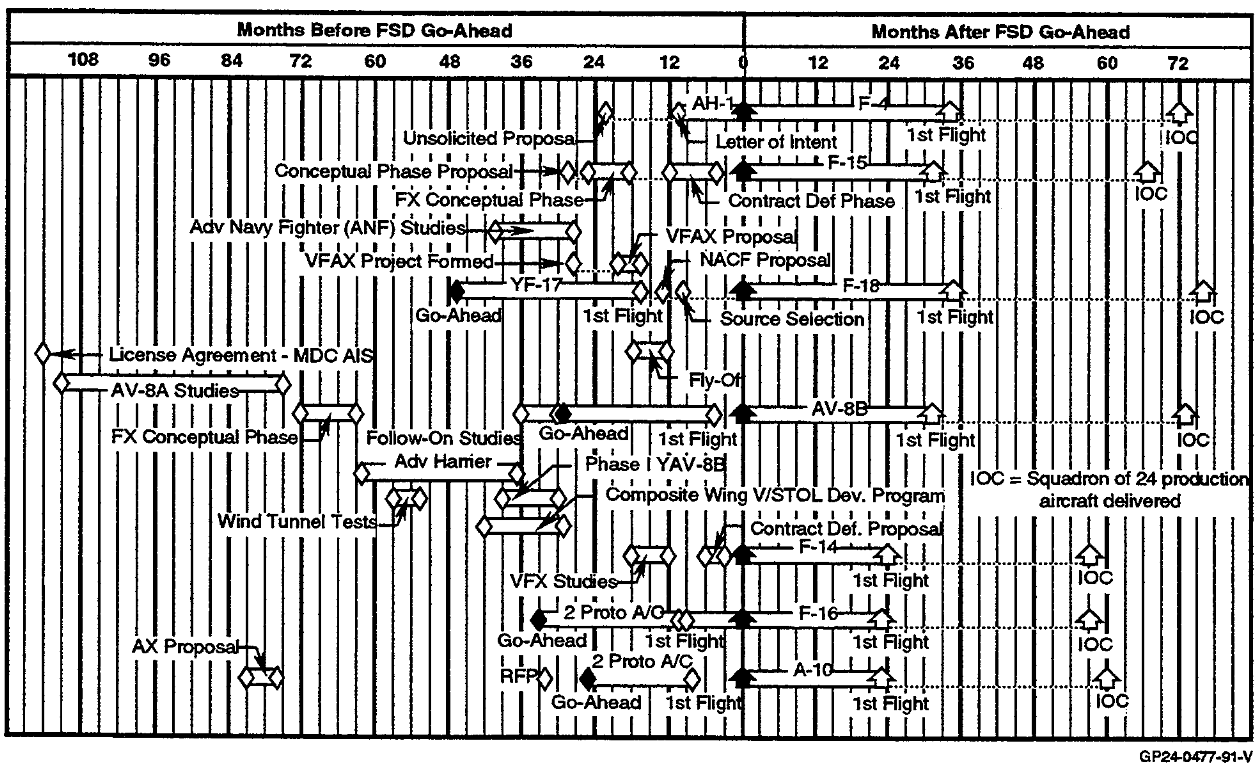


Figure 84. Fighter Aircraft Development Program Experience

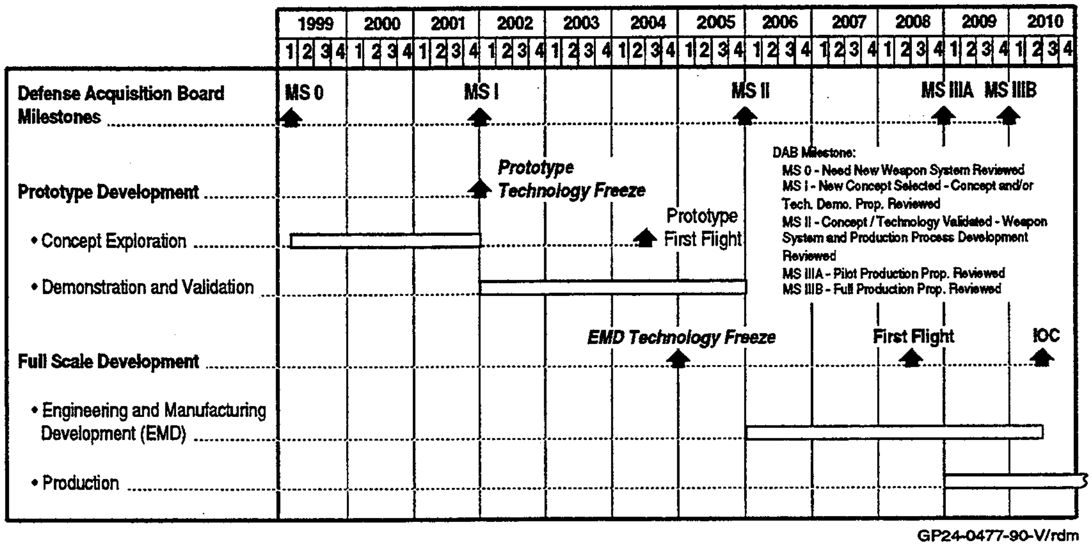
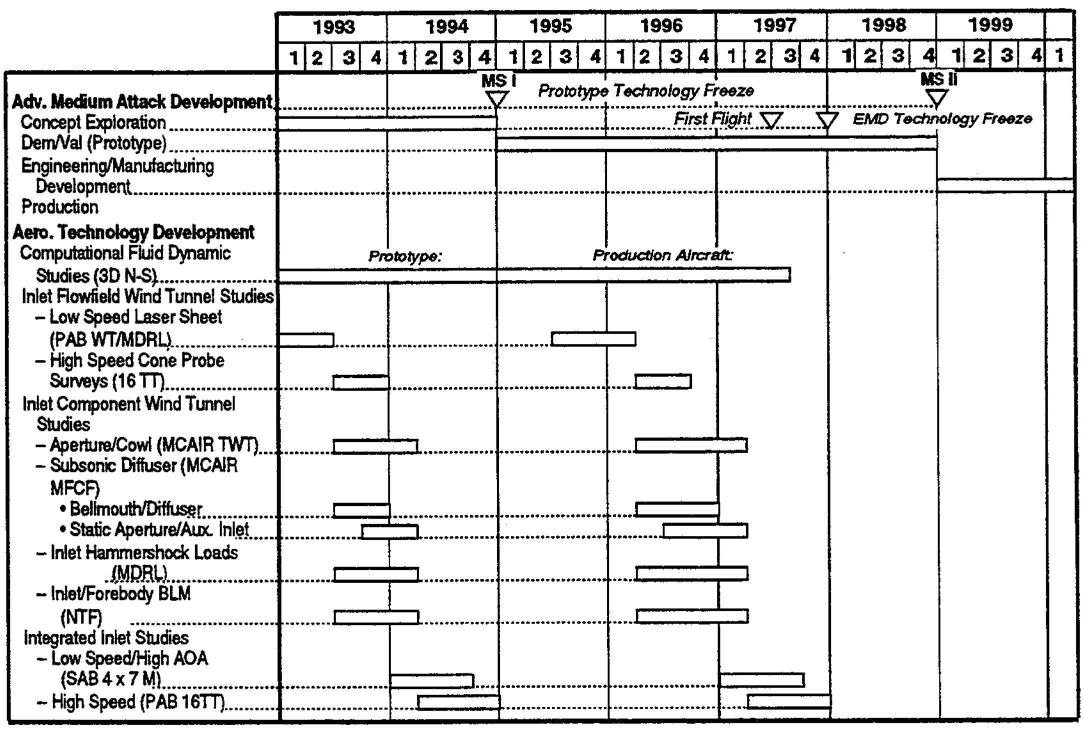


Figure 85. Typical Military Aircraft Development Schedule



Facility Codes:
PAB WT – NASA LaRC PAB Water Tunnel
MDRL – McDonnell-Douglas Research Labs Low Turbulence Wind Tunnel, Hammershock Test Facility
16 TT – NASA LaRC PAB 16 ft Transonic Wind Tunnel
TWT – MCAIR Trisonic Wind Tunnel (1 ft)
MFCF – MCAIR Mass Flow Calibration Facility
NTF – NASA LaRC National Transonic Facility
4 x 7 M – NASA LaRC Low Speed Wind Tunnel

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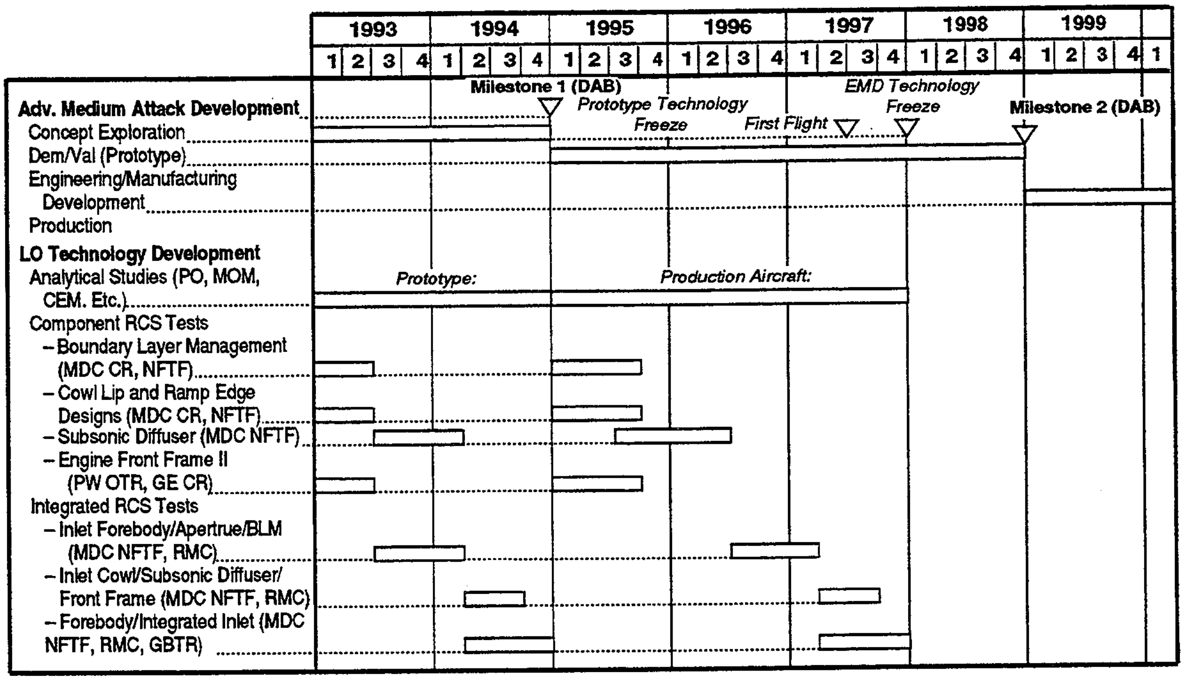
Figure 86. AMA Air Induction System Aerodynamic Technology Roadmap - 2005 IOC



Facility Codes:
MDC CR – MDC Compact Radar Range
NFTF – MCAIR Near Field Test Facility
PW OTR – Pratt & Whitney Outdoor Test Range
GE CR – General Electric Compact Radar Range
RMC – MDC Radar Measurement Center (San Diego)
GBTR – MDC Grey Butte Outdoor Test Range

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Figure 87. AMA Air Induction System LO Technology Roadmap - 2005 IOC

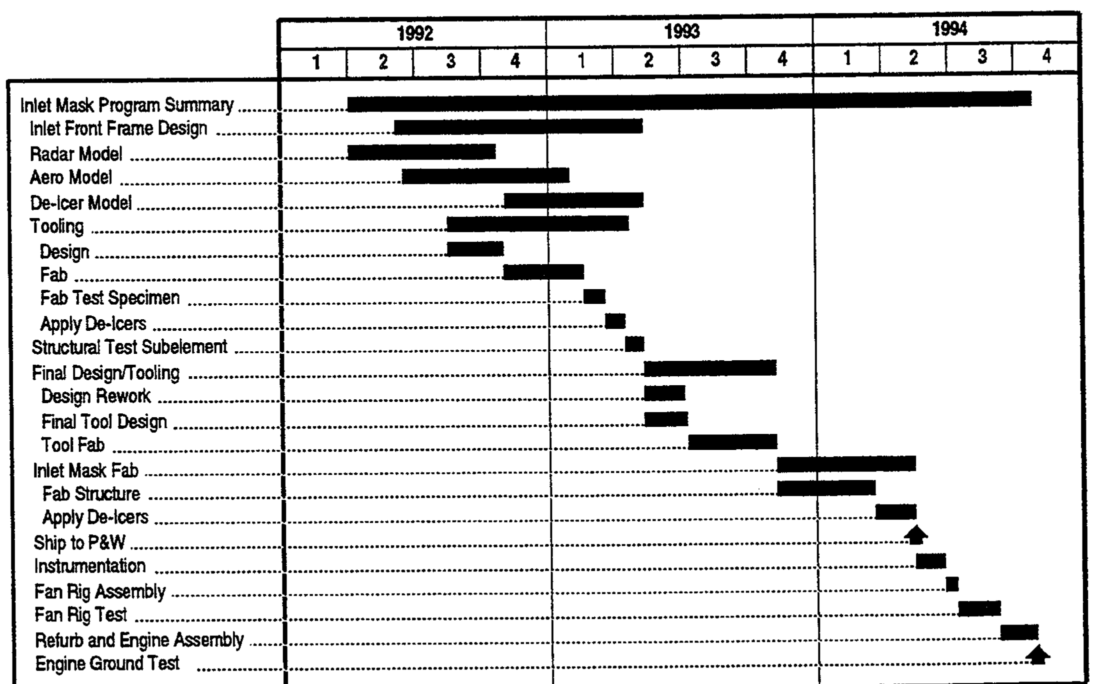

Figure 88. AMA Front Frame Technology Roadmap - 2005 IOC

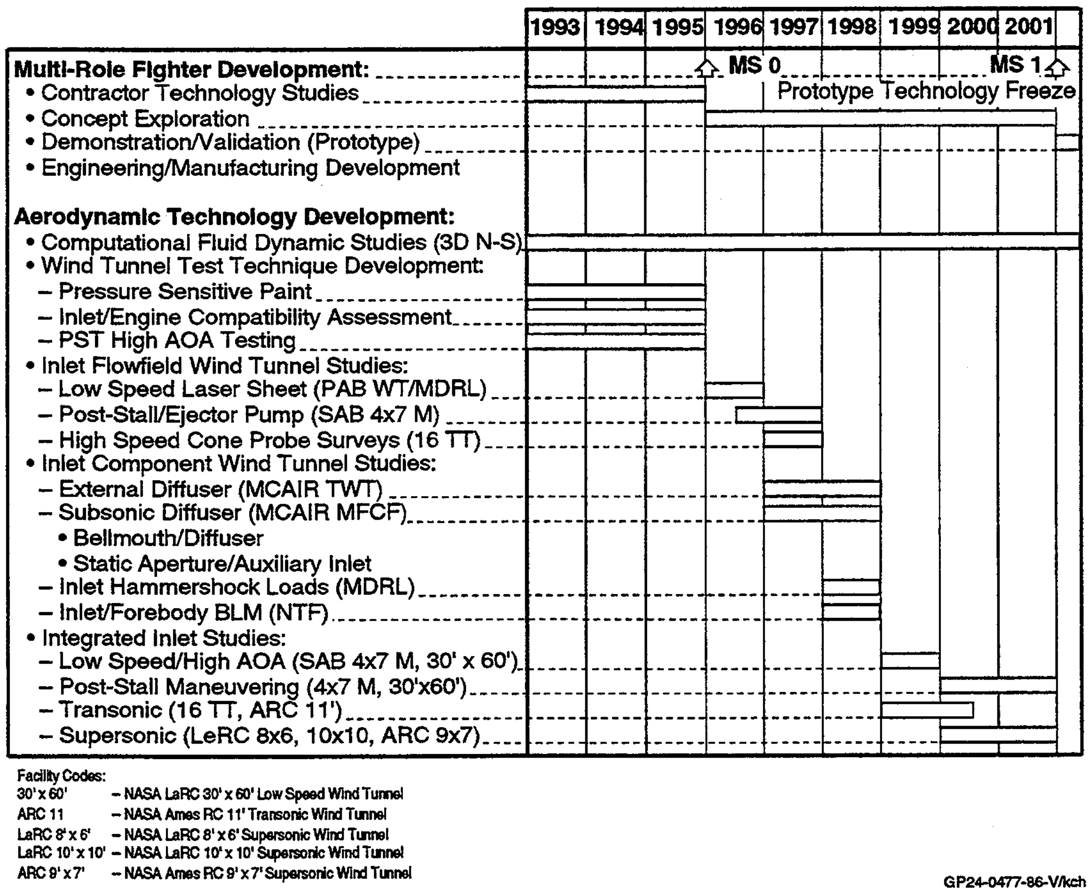

Figure 89. MRF Aerodynamic Technology Roadmap - 2010 IOC

Each technology roadmap represents a comprehensive aerodynamic and LO integration (RCS) development plan including a series of graduated risk component and integrated tests which utilize a number of different aerodynamic and RCS test facilities and techniques. Aerodynamic development begins with full three-dimensional Navier-Stokes Computational Fluid Dynamic (CFD) analysis of the entire propulsion flowfield, from the nosetip to the engine face. To supplement and validate the difficult external flowfield solutions about LO forebodies, one or two flowfield tests may be performed to better understand the inlet approach flowfield. These tests are optional for many installations, but probably mandatory for top-mounted inlet concepts. Low speed flowfield visualization tests are performed using water tunnel or vapor-seeded low turbulence wind tunnel laser sheet techniques to quantify the location and extent of forebody and/or wing-shed vortices and separation zones with potential to impact the inlet approach flowfield. High speed flowfield surveys are then accomplished using traversing cone probes, vapor screen, or laser sheet techniques to verify the low speed results and to quantify dynamic pressure and Mach No. effects. Flowing nacelles must be used to assess the impact of the inlet itself on the flowfield.

Concurrent with these efforts, tests of the isolated inlet, subsonic diffuser and inlet/forebody boundary layer management (BLM) components are completed in low cost facilities to assess component performance and need for design changes prior to large-scale integrated testing. Typical low cost facilities used by MCAIR for this testing include the Trisonic Wind Tunnel (TWT), a 1' x 1' Mach 2.0-capable high pressure, blowdown wind tunnel for inlet and BLM testing, and the Mass Flow Calibration Facility (MFCF), a high pressure static facility for diffuser and bleed system testing. Another important low cost test facility is a small-scale inlet hammershock simulator for assessing dynamic wall pressure loads in arbitrary ducts,

(serpentine, bifurcated, etc.). This facility couples a small-scale bellmouth diffuser model to a shock tube hammershock simulator.

The results of the flowfield testing and isolated component testing are "married" in integrated inlet test and analysis studies. This is the area for which little data currently exists. For a transonic attack aircraft, wind tunnel testing of the complete forebody/inlet/diffuser and operating BLM would take place in two wind tunnels, a very large low speed facility such as the NASA LaRC 4 by 7 meter tunnel for static and high AOA conditions and in a large transonic facility such as the NASA LaRC 16TT tunnel for transonic cruise and maneuver conditions. For a supersonic fighter concept, a third test set in a large supersonic wind tunnel, such as the AEDC Propulsion Wind Tunnels (16T and 16S) is required to validate external diffuser, and forebody/inlet boundary layer management. These tests are typically the last step in the propulsion systems aerodynamic development prior to flight test. In a generic technology development effort, these tests can also serve to validate inlet design guidelines, CFD development, and low cost isolated test techniques. This validation database is essential to reducing specific configuration moldline definition risk prior to integrated model design/fabrication efforts. A preliminary aerodynamic test plan for MRF and AMA integrated inlet wind tunnel testing is presented in Figures 90, 91, and 92. MRF testing is accomplished in three test phases concentrating on post-stall maneuvering, transonic cruise and maneuver performance, and supersonic dash performance MRF inlet. Configuration and flight condition parametrics and typical parameter ranges are listed in Figure 90. Similar information is provided for a two test phase AMA program in Figure 91. Inlet test data of primary interest is listed in Figure 92, and consists of primarily static, total and dynamic (turbulence) pressures. The primary measure of inlet/engine compatibility is dynamic distortion which is assessed by computing industry standard statistics such as IDR, IDC and IDCMAX using temporal measurement techniques and algorithms to capture the maximum range of time-varying pressure variation across the engine face, Reference 13, 16.

Parameter	Post-Stall	Transonic	Supersonic
Mach Number	0 – 0.25	0.6 – 1.3	1.4 – 1.8
Angle-of-Attack	-30° – 90°	-10° – 35°	-5° – 15°
Angle-of-Sideslip	0° – 45°	0° – 15°	0° – 5°
Mass Flow Ratio (MFR)	0.4 – 1.0	0.4 – 1.0	0.6 – 1.0
Diverter Height	0.75 δ	0.75 δ	0.4 – 1.0 δ
Cowl Lip Radius	0.1", 0.5", 1.0"	0.1", 0.5", 1.0"	0.1", 0.5", 1.0"
Cowl Lip Droop Angle	0°, 20°, 40°	0°, 20°	0°
Inlet Bleed Mass Flow (Percent of Total Flow)	–	3%	0% – 5%
Diverter Mass Flow	–	0% – 20%	0% – 20%
Auxiliary Inlet Area	0, 0.5, 1.0 A_t	0, 0.5 A_t	0 A_t
Diffuser Offset	Low, High	Low, High	Low, High

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Figure 90. MRF Aerodynamic Test Plan
Integrated Inlet Model

Parameter	Low Speed	Transonic
Mach Number	0 – 0.25	0.6 – 1.2
Angle-of-Attack	-5° – 30°	-5° – 30°
Angle-of-Sideslip	0° – 10°	0° – 10°
Mass Flow Ratio (MFR)	0.4 – 1.0	0.4 – 1.0
Right Hand Inlet MFR	0.4, 0.7	0.4, 0.7, 1.0
Secondary Airflow Ratio	0% – 15%	0° – 15°
Diverter Height	0.5 δ	0.5 δ – 1.0 δ
Auxiliary Inlet Area	0, 0.25, 0.5 A_t	0, 0.25 A_t
Diffuser Offset	Low, High	Low, High

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Figure 91. AMA Aerodynamic Test Plan
Integrated Inlet Model

- Off-Body Flowfield Conditions:
  - Mach Number, Recovery (PT), Local AoA/Beta
- Forebody Boundary Layer Characteristics:
  - Upstream/Downstream, Velocity vs Height
- Inlet Ramp Static Pressure Distribution
- Inlet Throat Total Pressure Profiles
- Subsonic Diffuser Static Pressure Distribution
- Engine Face Flowfield Characteristics:
  - Total Pressure Profile
  - Static Pressure Profile
  - Dynamic Pressure Profile
- Engine and Secondary Mass Flow Rates
- Bleed Mass Flow Rates
- Calculated Parameters:
  - Boundary Layer Heights (Total, Displacement, Momentum)
  - Throat Recovery, Total Pressure Map
  - Engine Face Recovery, Total Pressure Map
  - Engine Face Compatibility Statistics: (IDC, IDR, IDCMAX, Planar Turbulence)

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Figure 92. Inlet Test Data Requirements

4.3 DESIGN REFINEMENT USING CFD

The development of a high payoff, low risk wind tunnel model design must begin with refinement and validation of the basic configuration external and internal moldlines **prior** to high cost model fabrication activities. To accomplish this, the process illustrated in Figure 93 must be followed. The process begins with the inlet conceptual designs developed during conceptual design trade studies. These designs are then matured by careful definition of all surfaces, edges and contours. All flow areas, bleed areas and other features are established using data from previous component testing. Finally, all surfaces are mathematically defined to allow CFD grid, NASTRAN and numerical-control (NC) machine path generation.

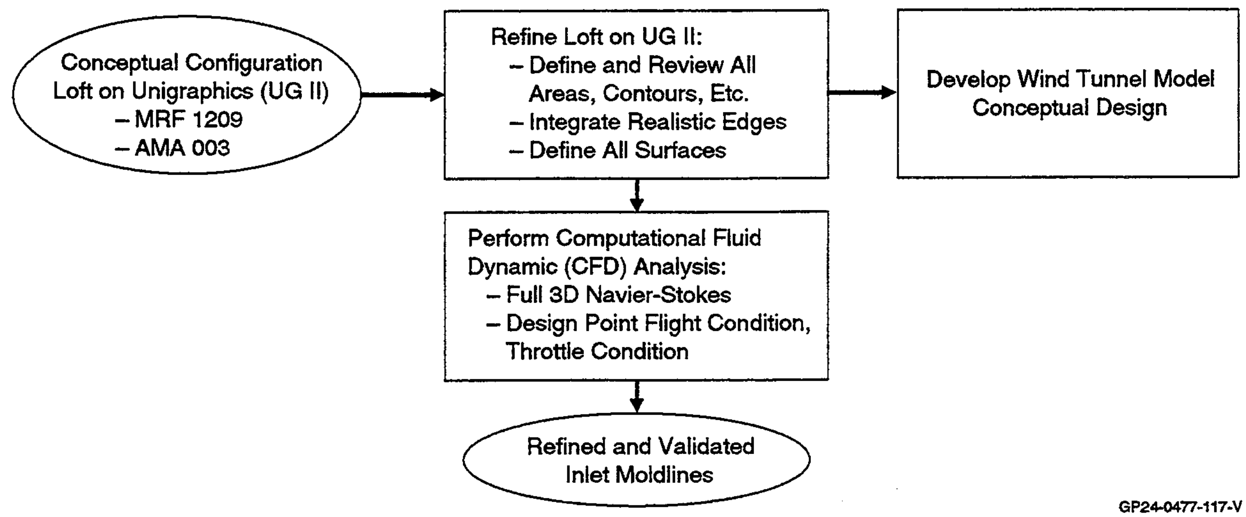


Figure 93. Configuration Moldline Refinement Process

Currently, the only tool available to assess the integrated aerodynamics of LO inlet/airframe moldlines, **prior** to test is full configuration CFD analysis. A full configuration CFD analysis is complex and must follow a process similar to that outlined in Figure 94. This process starts with the detailed, "surfaced" CAD geometry which is then "cut" into structured-grid compatible elements. Once this is complete, the CFD analyst establishes a multi-block grid "architecture", develops meshes about the entire configuration, and develops the block-to-block coupling relationships. At the same time, the analyst must establish the flow conditions at all far field boundaries including the engine, bleed and secondary airflow "outflow" boundaries. This

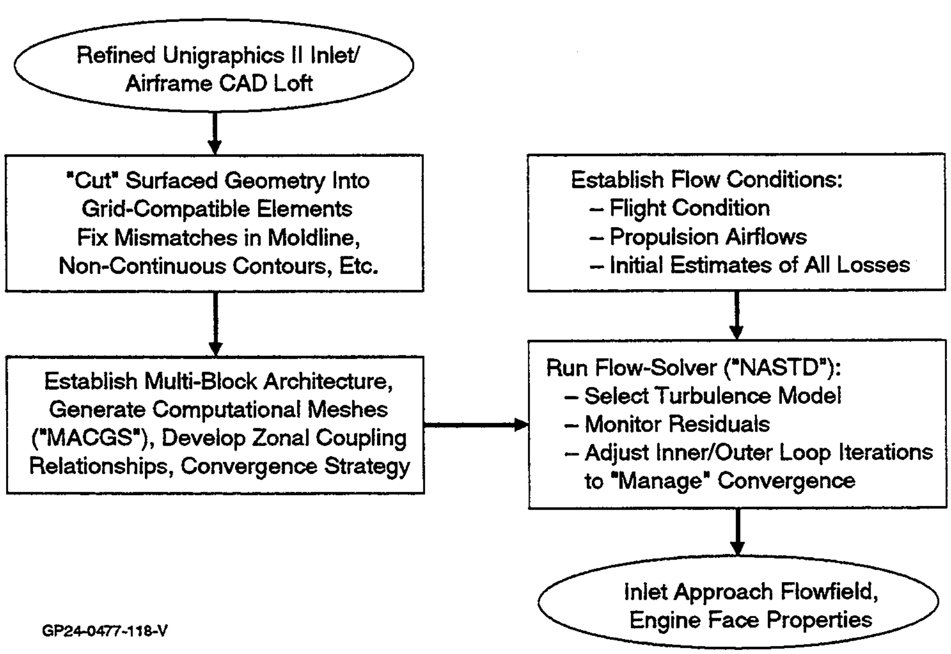


Figure 94. Computational Fluid Dynamic Analysis

requires an initial estimate of the propulsion system total pressure losses. Finally, the analyst runs the flow-solver to develop a multi-block, full configuration solution. This requires selection of an appropriate turbulence model, monitoring of all zonal solution residuals, and adjustment of inner zone iteration and zone-to-zone boundary condition data exchanges to bring all zones to convergence uniformly.

To validate the MRF 1209 and AMA 003 internal and external moldlines, full configuration CFD solutions were generated at each aircraft's design flight condition, using the process outlined above. Large-scale multi-block grids were developed using the McDonnell Aircraft Computational Grid System (MACGS). Flow properties at all inlet/airframe area of interest were then generated using the MDC Navier-Stokes Time-Dependent (NASTD) CFD code. These tools are described in detail in the following sections.

4.3.1 MACGS Grid Generation System – MACGS is a general purpose grid generation tool for complex configurations. This system was developed primarily for Computational Fluid Dynamics (CFD) applications, but suitable grids can be generated for virtually any application requiring a structured array of points in a defined region. This system can be used to generate grids for two or three dimensional configurations. Key features of the system are an interactive graphics user interface and the ability to generate complex multi-block grids.

The surface definition for both the MRF 1209 and AMA 003 configurations were obtained from Unigraphics (UG) files. Grid points were distributed over the surface and clustered to resolve areas of high curvature and discontinuities. Multi-block grid topologies were developed to model each component (forebody, inlet, diffuser, etc.) of each configuration individually. With this approach, the mesh is designed to optimally resolve flow gradients on each component.

The MRF 1209 surface grid is illustrated in Figure 95. Details of the MRF 1209 inlet surface and off-body grids are illustrated in Figure 95A. This grid consists of 9 blocks containing over 534,000 points. The computational blocks are all structured , either as Cartesian, "H" grids, Radial "C" grids, or, for the inlet duct, Polar grids in which a singularity point set runs down the approximate centerline of the duct. These singularity points are treated using a special boundary condition whereby all flow properties are calculated using linear interpolation of all surrounding points. The MRF 1209 multi-block grid architecture is summarized in Figure 95A.

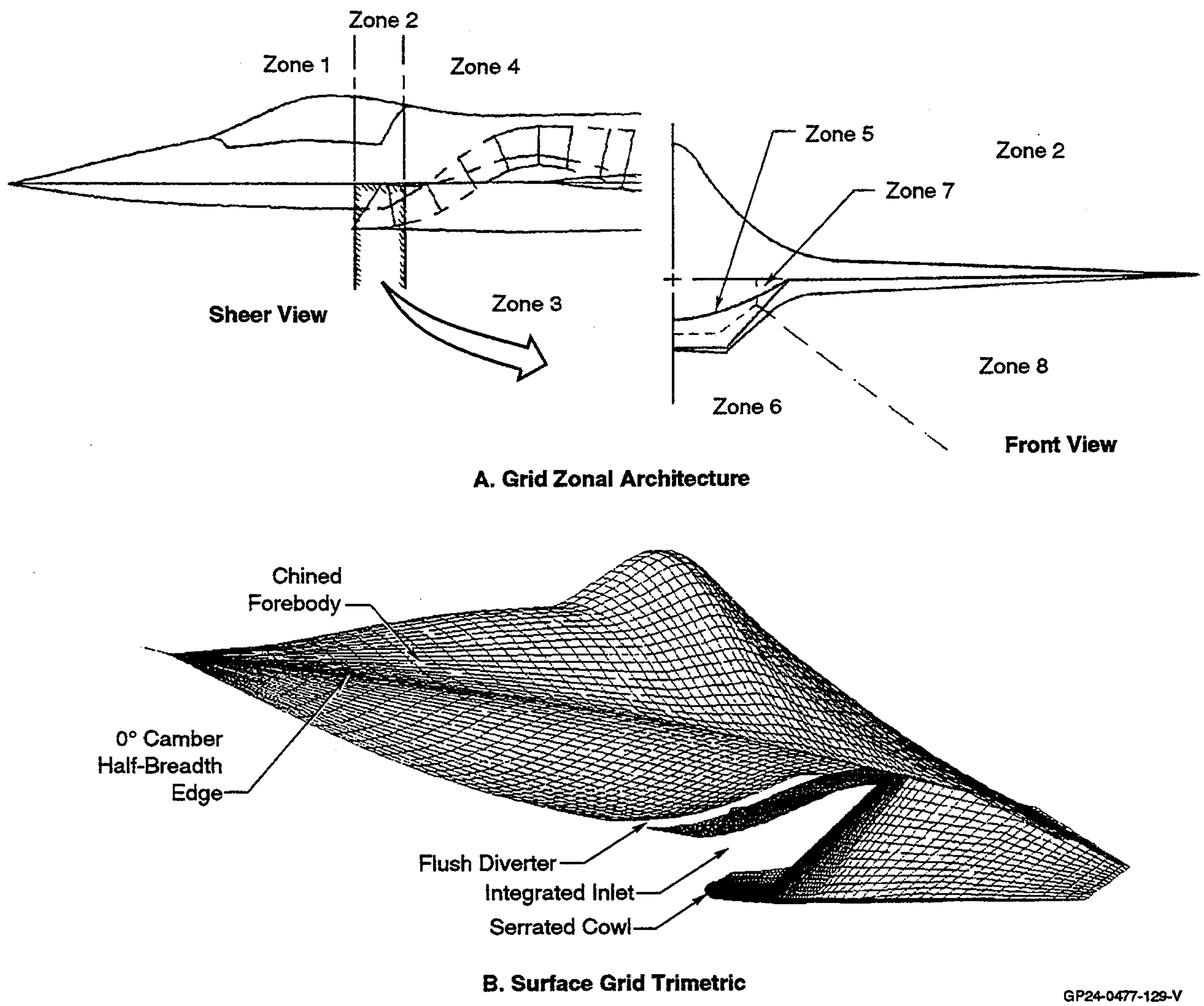


Figure 95. MRF 1209 Multi-Zone Surface Grid

The AMA 003 surface grid is illustrated in Figure 96. Details of the AMA 003 inlet and diverter surface and off-body grids are illustrated in Figure 96A. This grid consists of 13 computational blocks containing over 660,000 blocks. A particularly challenging portion of this geometry was the side-mounted external diffuser, which was completely modeled to insure flowfield simulation fidelity.

4.3.2 NASTD Flow Solver – The McDonnell Douglas Navier-Stokes Time Dependent Code (NASTD) is a Reynolds-averaged computational fluid dynamics (CFD) code used for the calculation of Newtonian gas (air, e.g.) flowfields about arbitrary geometries. It is a multi-zone code which can be run in two or three dimensions for internal or external, subsonic, transonic, supersonic of hypersonic viscous or inviscid flows on MACGS-structured grids.

All Navier-Stokes terms are retained in the governing equations, including secondary flow, reversed flow convection, pressure gradients normal to wall, and streamwise diffusion. All heat transfer terms are retained. For these studies, effects of turbulence are modeled using the Baldwin-Lomax algebraic turbulence model. Modification of the effective heat transport coefficient due to turbulence is linked to the momentum diffusion coefficient by a turbulent Prandtl number, which is taken to be constant.

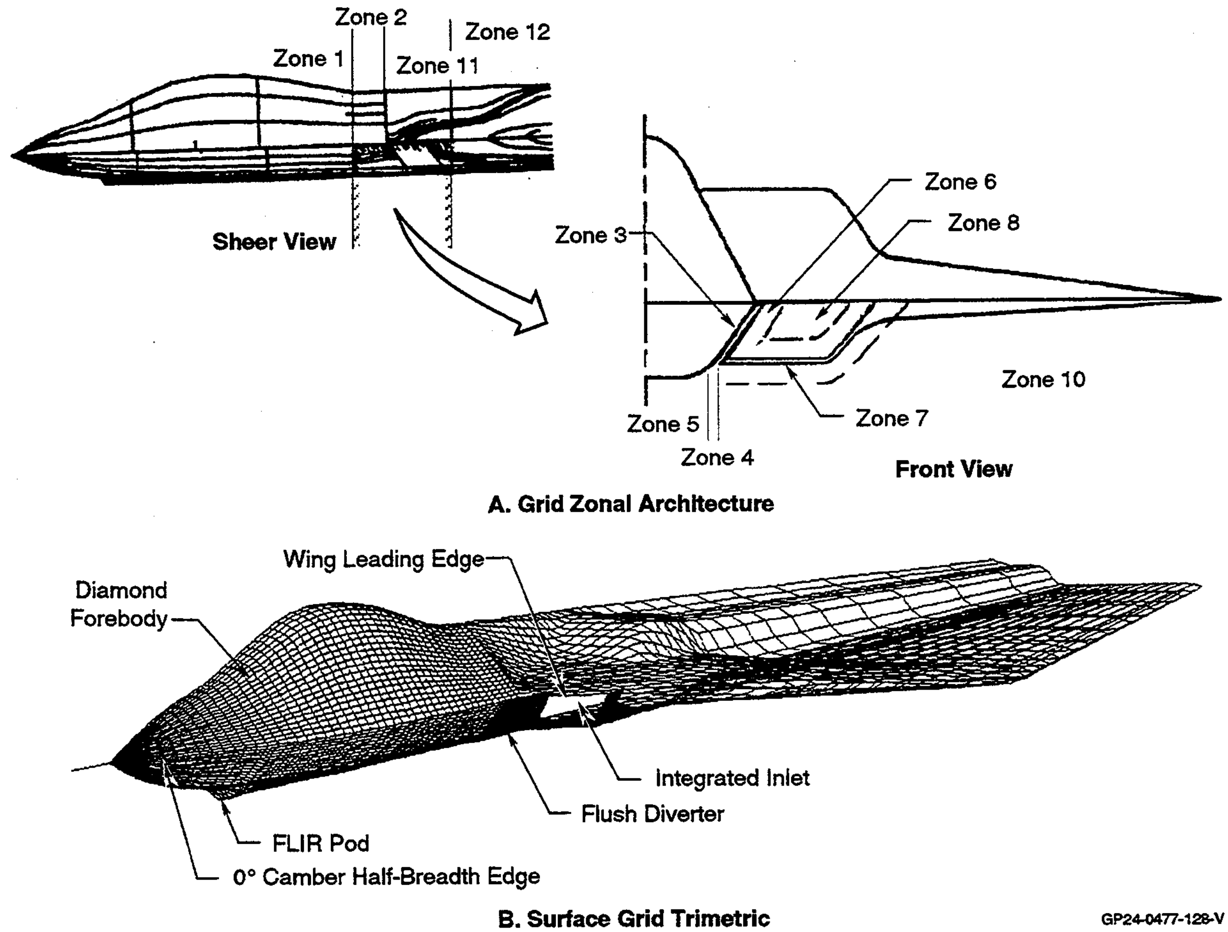


Figure 96. AMA 003 Multi-Zone Surface Grid

The solution is executed iteratively on each zonal computational mesh to satisfy input boundary conditions. The flow equations are evaluated using second-order-accurate finite differences. The partial differential equations are modeled in their conservative form. The explicit terms are computed using upwind or central differencing. The implicit terms are computed using an approximately factored scheme.

For a multi-block solution, the boundary conditions on each block interface are fully-coupled to the adjacent blocks, and updated after every five to ten iterations. Convergence of the "global" solution is "managed" by staging the convergence of each computational zone and then monitoring the equation residuals.

4.3.3 Inlet/Airframe Flowfield Solutions – The MRF 1209 was analyzed at Mach 1.6, 0° AOA, at a unit Reynold's No. of 2.5 million per foot. The geometry was analyze at model scale, (9.9%). The inlet mass flow ration (MFR) was set at the design point, giving an inlet throat Mach No. of .767. The diverter was controlled by setting its outflow plane static pressure to one-tenth of ambient, insuring "started" supercritical flow through the diverter entrance.

Forebody flowfield characteristics are illustrated in Figure 97. Smooth, unseparated flow dominates the lower forebody flowfield, with no evidence of vorticity in the inlet approach flowfield. The fuselage boundary layer is adequately removed by the 2.1" (full scale) flush boundary layer diverter. Inlet ramp normal shock/boundary layer interactions are controlled using ramp boundary layer bleed. Bleed is simulated on the ramp surface through use of a special boundary condition in a zone from the diverter leading edge to just aft of the cowl lip. The bleed is fixed at 5% of the captured airflow.

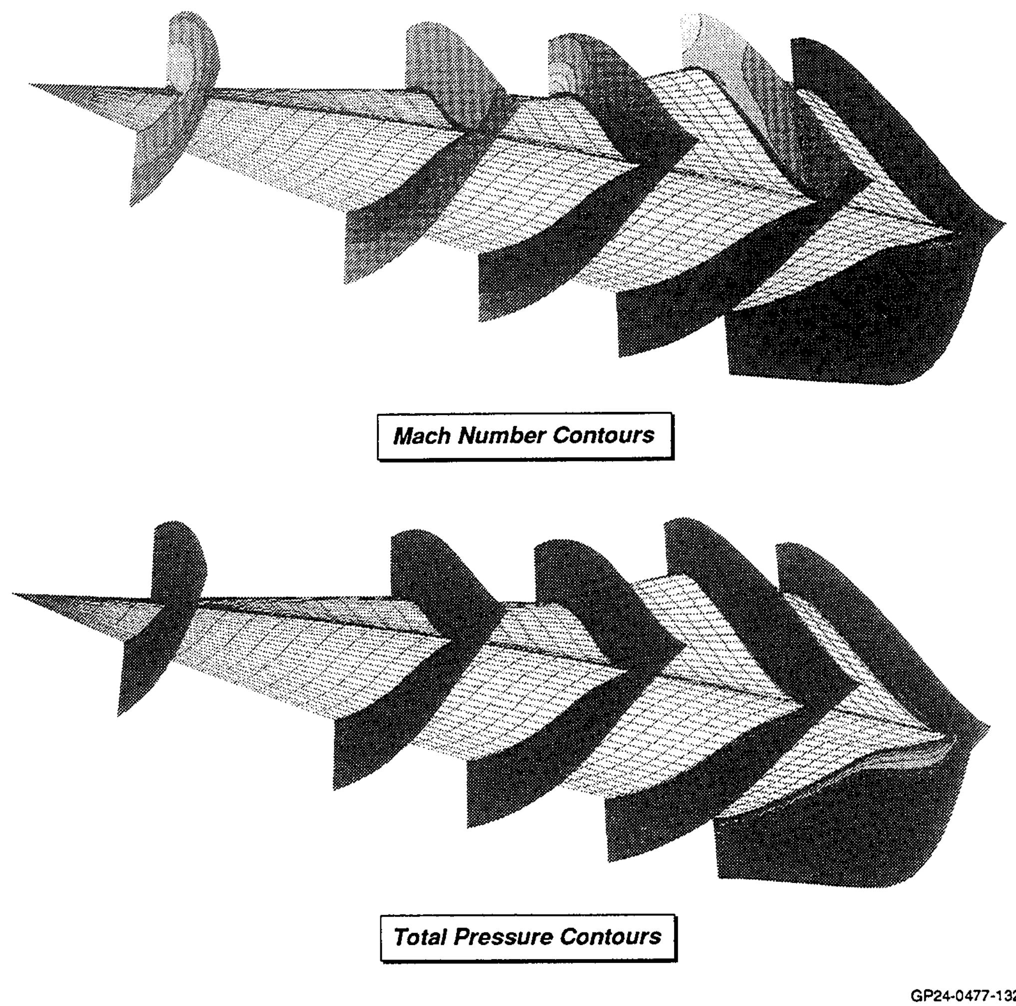
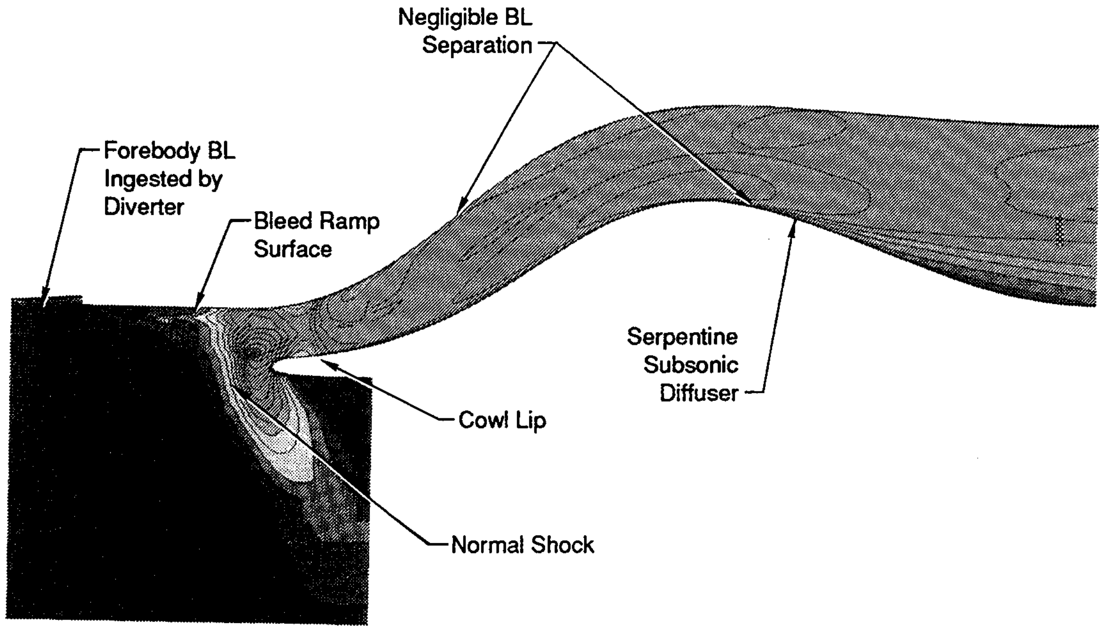


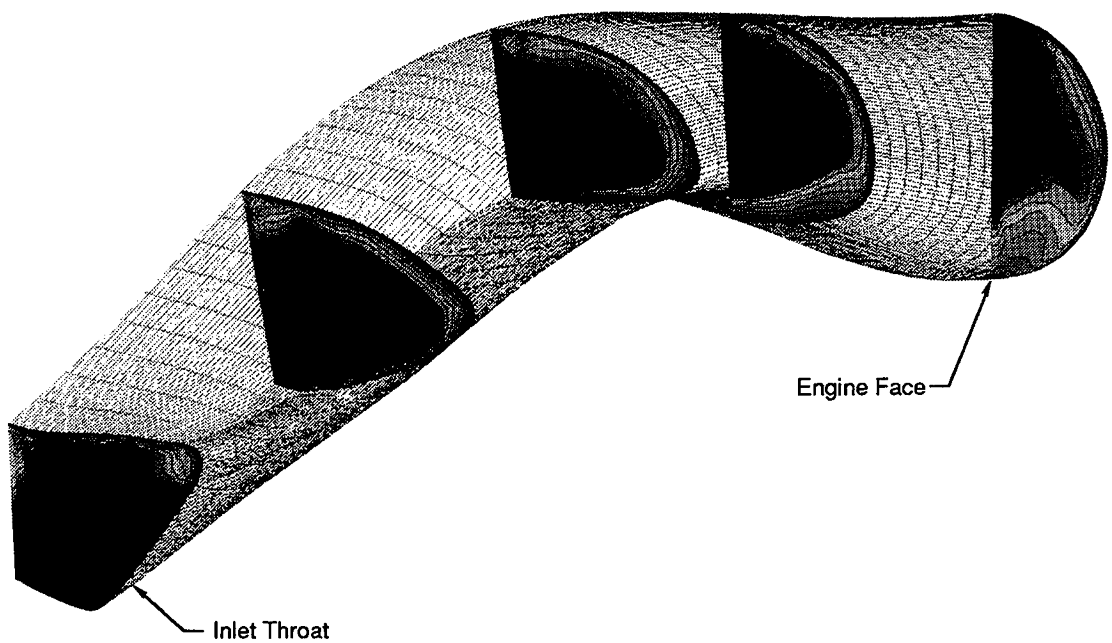
Figure 97. MRF 1209 Inlet Approach Flowfield

Inlet diffuser and engine face Mach No. contours are illustrated in Figure 98. The external compression normal shock sits on the splitter plate just forward of the .75" lip radius serrated cowl, Figure 98A. Normal shock/boundary layer interactions thicken the boundary layer, but do not appear to cause any serious inlet or diffuser separations. Serpentine diffuser flows are well-behaved with no evidence of significant separation, Figure 98B.

The AMA 003 was analyzed at Mach 0.85, 0° Angle-of-Attack (AOA), at a unit Reynold's No. of 5 million per foot. The geometry was simulated at model scale, (12.5%). The inlet mass flow ratio (MFR) was set at the design point, giving an inlet throat Mach No. of .767. The AMA 003 inlet approach flowfield is illustrated in Figure 99. Mach number and total pressure contours indicate a clean, unseparated flowfield with little or no vorticity induced by the sharp forebody half-breadth. Total pressure contours indicate a boundary layer slightly thicker on the fuselage top than on the bottom, and within the capability of the 1.75": (full scale), diverter. Boundary layer particle traces are illustrated in Figure 99C. These traces show fairly uniform boundary layer behavior, with marked dispersion around the canopy topside and just below the chine on the fuselage bottom. Significantly, no separation occurred due to the forebody chin pod installation.



**a) Inlet Ramp/Diffuser Mach Contours
Centerline Sheer Cut**



**b) Subsonic Diffuser/Engine Face Total
Pressure Contours**

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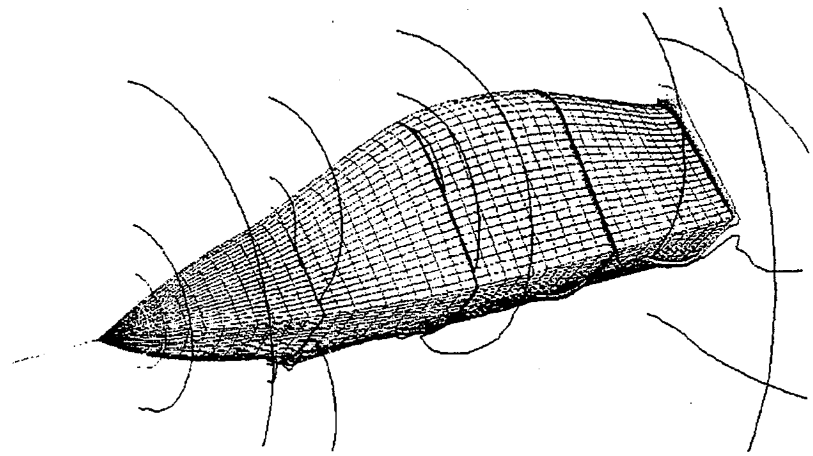
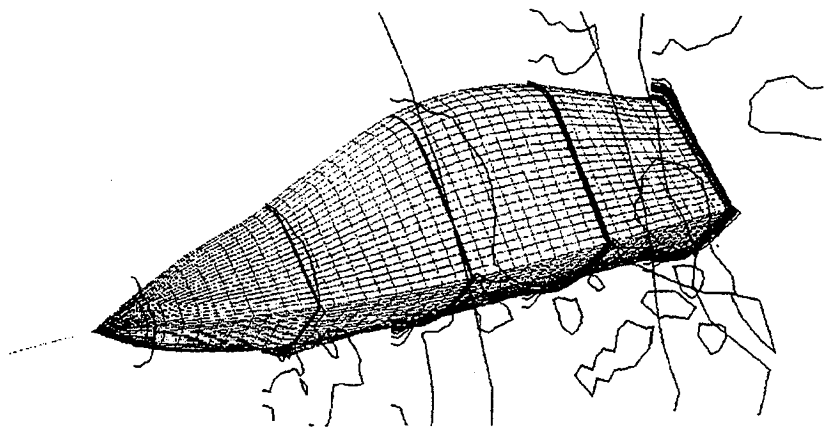
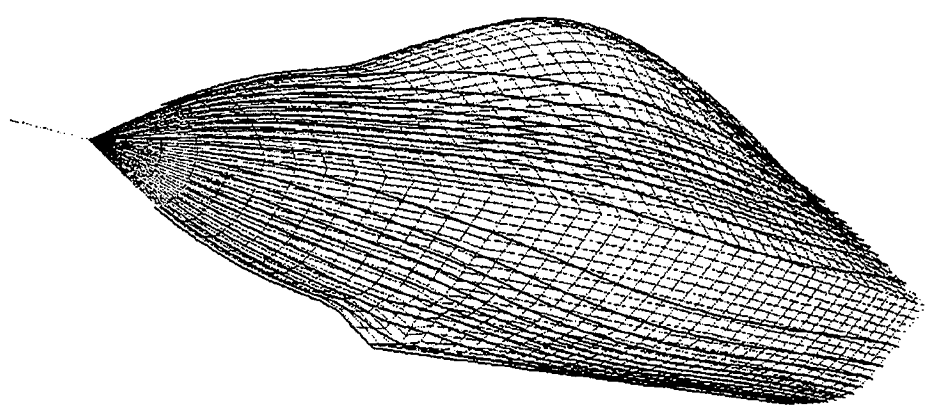
Figure 98. MRF 1209 Engine Face Contours



A. Mach Number Contours



B. Total Pressure Contours



C. Surface Particle Traces

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Figure 99. AMA 003 Inlet Approach Flowfield

Installed inlet diffuser flowfields are shown in Figure 100. As can be seen, the inlet throat flow is dominated by a large stagnated flow region on the upper cowl surface. This disturbance propagates downstream, disturbing the diffuser flow on both the upper and lower walls, and resulting in a large, low pressure region on the compressor lower face. This behavior is significantly different from that observed for the uninstalled diffuser, Figure 54. This is a strong indication of the sensitivity of serpentine diffuser aerodynamics to inlet throat conditions, and of overall inlet design to integrated effects. The source of the flow separation is the upper cowl integration and edge shape, Figure 101. At 0° AOA, the forebody boundary layer is reasonably well behaved, however at the wing/fuselage junction, the wing induces a significant downwash which puts the flowfield at the wing leading edge at an appreciable negative local AOA, Figure 101. This, combined with the sharp edge, results in a large three-dimensional separation on the center and outboard upper cowl lower surface. This separation cascades downstream into the diffuser throat, resulting in serpentine diffuser stall. Subsequent CFD solutions, generated at 5° AOA, show no such separation.

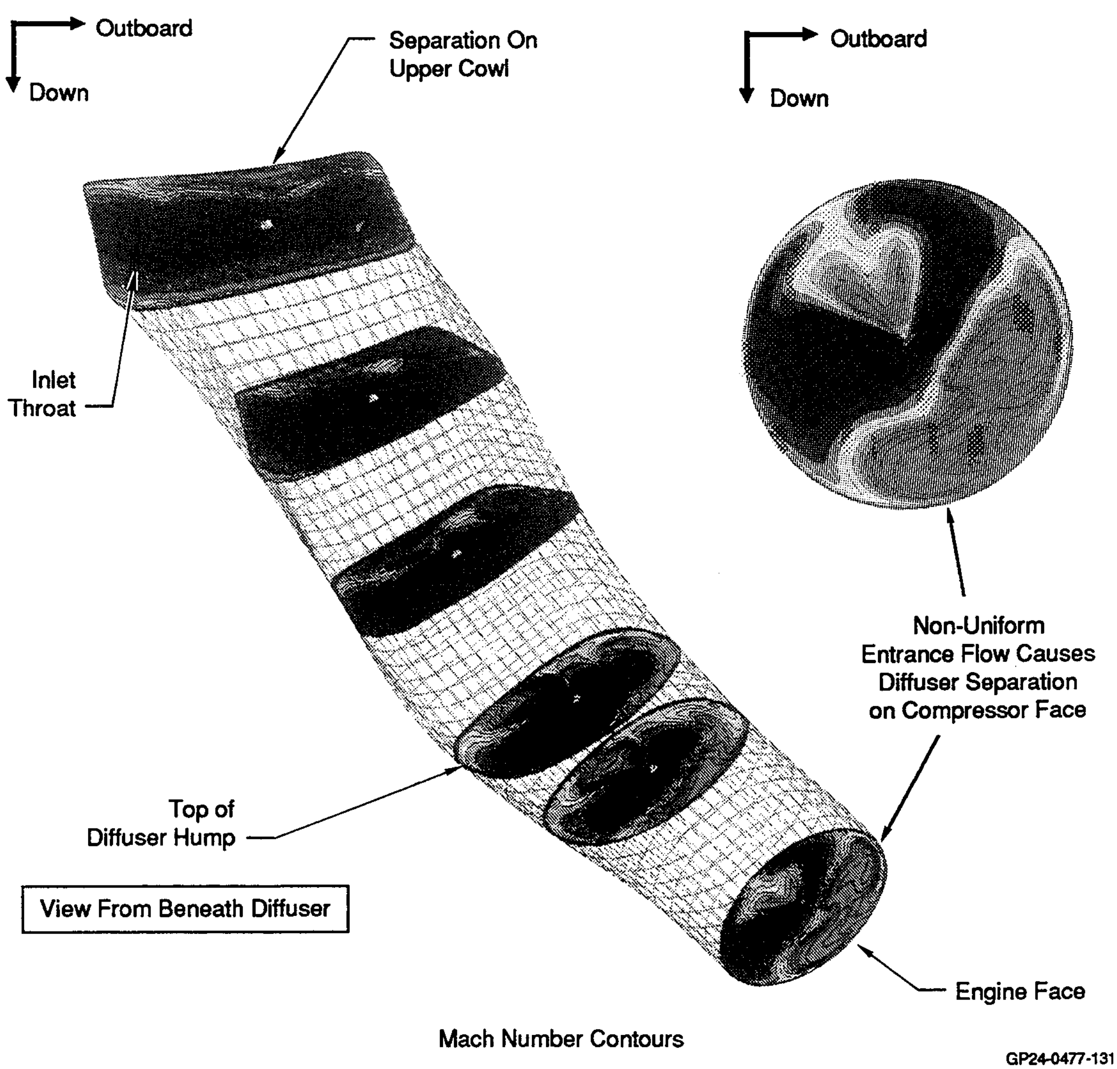
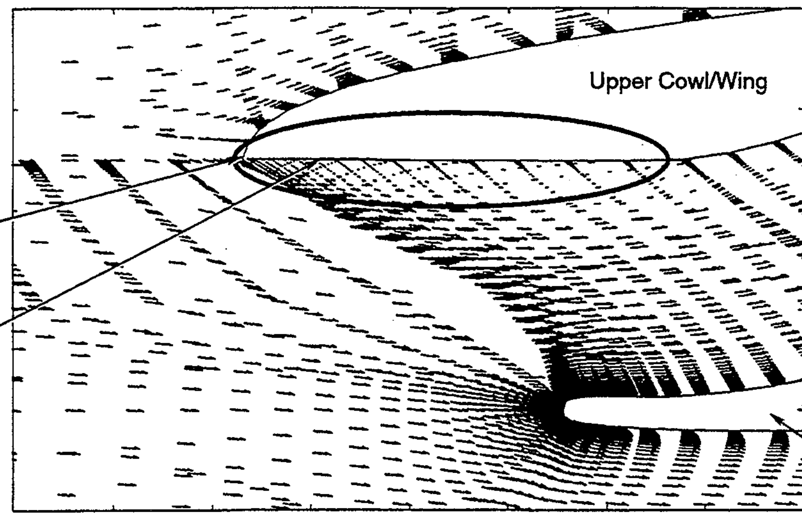
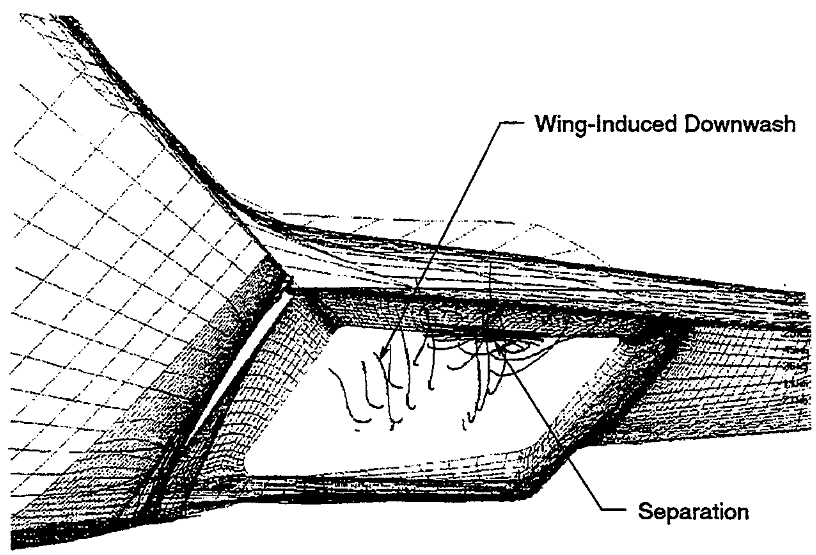


Figure 100. AMA 003 Inlet/Diffuser Flow



A. Flowfield Velocity Vector Cross-Section



B. Particle Traces

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Figure 101. AMA 003 Inlet Flowfield Separation

The validity of this solution is suspect because of the assumptions used in the CFD code turbulence model. The Baldwin-Lomax algebraic turbulence model tends to exaggerate the extent and severity of small-scale boundary layer separations, particularly in the presence of adverse pressure gradients. In addition, the model, developed for thin, attached boundary layers, does not allow prediction of subsequent boundary layer re-attachment phenomena. As a result, it is probable that the diffuser stall predicted by the CFD code is much more severe than would occur in nature. Any cowl separation and resultant diffuser aerodynamic anomalies can be avoided by adding a small amount of bluntness to the upper cowl leading edge. This bluntness should be added as a parametric to any integrated inlet model test, to confirm this sensitivity.

The MRF 1209 and AMA 003 integrated inlet flowfield characteristics analyzed with CFD illustrate the criticality of integrated inlet analysis and wind tunnel testing. Small features such as cowl lip shape or forebody camber can have very large impacts on overall performance, particularly for LO-configured aircraft concepts. Parametric, integrated analysis and testing is therefore a requirement for insuring success in developing low risk air induction system moldline definitions.

4.4 WIND TUNNEL MODEL DESIGN

Two integrated wind tunnel model concepts were designed to meet the aerodynamic database requirements outlined in Section 4.2 and to be compatible with NASA's large-scale test facilities and existing model hardware.

4.4.1 MRF 1209 Forebody/Inlet Wind Tunnel Model – To effectively generate integrated inlet performance and distortion data, a wind tunnel model must accurately simulate all surfaces forward of the inlet aperture, the inlet aperture and subsonic diffuser, and any boundary layer management devices on the forebody or inlet. To parametrically investigate integrated inlet design interactions, the critical air induction system components must be easily changed and any active devices must be independently controllable. This is particularly true for boundary layer management devices such as bleed or blowing or boundary layer diversion, and for critical trade issues such as cowl lip shape and planform, or subsonic diffuser obscuration.

A 9.95% MRF 1209 fighter inlet model concept compatible with all of these requirements is illustrated in Figures 102 and 103. This model consists of an LO forebody concept complete with chine and canopy, a parametric flush boundary layer diverter module, a parametric normal shock bleed ramp module, and a parametric cowl lip module, with interchangeable lip contours and lip droop settings. This parametric cowl lip also allows simulation of a variety of auxiliary inlet shapes and sizes to assess inlet high AOA recovery and distortion characteristics. Model diverter, bleed system and engine face mass flow rates are controlled with three separate mass flow plugs. The twin diverter and bleed system mass flow plugs are 1.944" diameter, electric-motor-driven plugs which exhaust to freestream. The 4.0" diameter engine face mass flow plug is an existing NASA design, Reference 36, which exhausts into an integrated ejector to allow full engine mass flow simulation at all simulated flight conditions.

This model concept is compatible with extensive pressure instrumentation. Up to 250 (+15 psid) model forebody static pressures (+15 psid) can be accommodated using internal and externally mounted Electronically-Sensed Pressure (ESP) modules. Parametric cowl lip modules can be fabricated with extensive throat station total and static pressure instrumentation. Use of a 4.0" diameter engine face allows use of an industry-standard 40 total (+15 psid) and dynamic (2000 Hz) pressure probe face rake positioned at the Aerodynamic Interface Plane (AIP).

The entire inlet model concept is mounted on a short strut which, in turn, mounts to an existing NASA 4" sting design, Reference 30. Use of this mounting system along with internal ESP modules and a bellows insert at the diffuser/engine face interface allows incorporation of a six-component force balance at the strut-sting interface with low interference pressure instrumentation "bridging" to measure throttle-dependent changes in inlet drag characteristics. Full inlet drag characteristics can then be assessed by referencing the data at a aerodynamic reference mass flow ratio measured on an appropriate aerodynamic force and moment model.

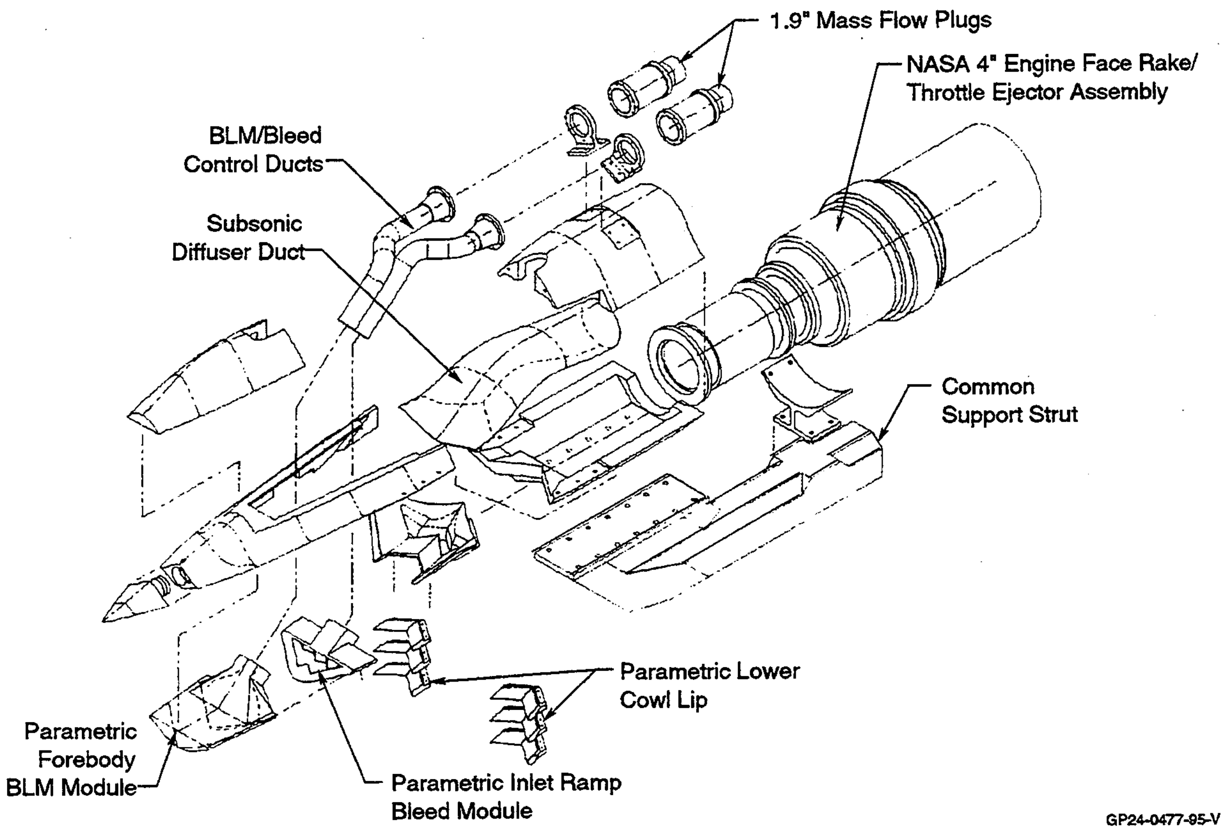

Figure 102. MRF 1209 Integrated Inlet Model Concept
Trimetric

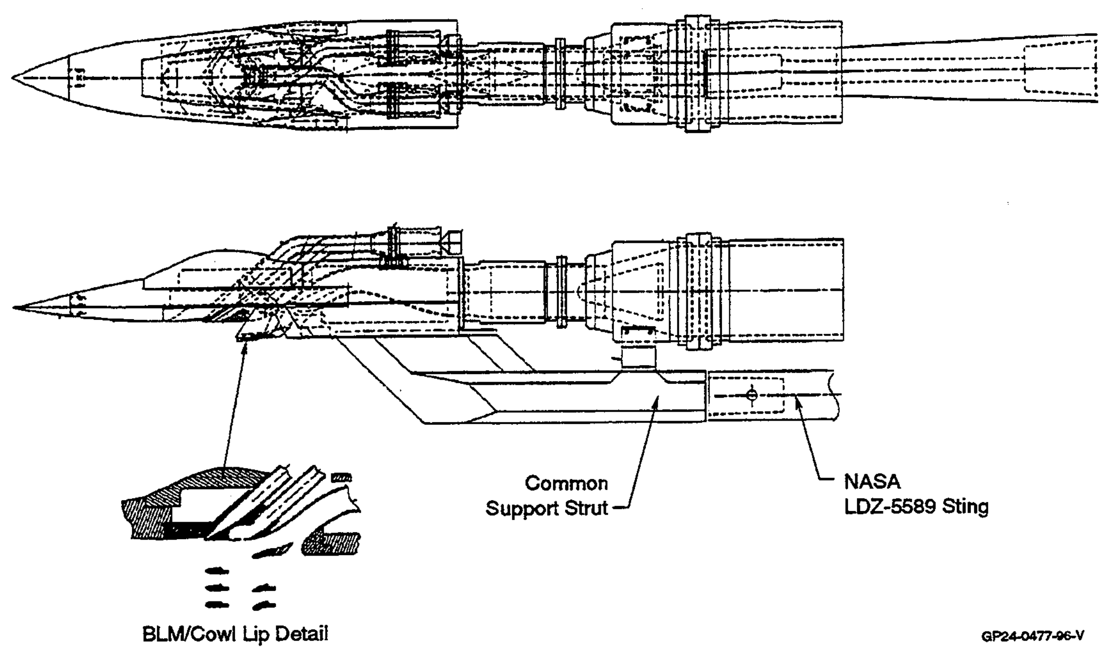

Figure 103. MRF 1209 Integrated Inlet Model
Plan and Sheer Views

4.4.2 AMA 003 Forebody/Inlet Wind Tunnel Model – A 12.5% AMA 003 inlet model concept compatible with the requirements discussed in Section 4.4.1 is illustrated in Figures 104 and 105. This model consists of a parametric forebody and canopy module, a center fuselage module, two serpentine inlet diffusers, two fixed geometry diverters and inlet modules, a single auxiliary inlet interface (on the left-hand inlet duct), and a annular secondary airflow system inlet and exhaust plenum. In this model, a 1.944" mass flow plug is used to control the secondary air flow system mass flow via four transfer tubes which transport inlet secondary flow from the secondary plenum, just upstream of the AIP, to the mass flow plug entrance, (not shown). The left hand inlet mass flow rate is controlled by a NASA 4" mass flow plug/ejector assembly, Reference 33. The right hand inlet is controlled by interchangeable fixed chokes, to assess right hand mass flow effects on left hand inlet performance and compatibility, and on throttle-dependent drag.

Use of a parametric forebody module concept allows low-cost examination of forebody geometry (camber, shape, etc.) effects on the inlet flowfield characteristics and installed performance. Interchangeable forebodies also allow parametric examination of inlet diverter design effects. Use of common sting-strut support components, mass flow plugs, and engine face rake with the MRF 1209 dramatically reduces model costs and development risks.

Pressure instrumentation on this model would include 250 static pressures (+15 psid) on the forebody and inlet aperture, and another 100 taps on the left and right electroformed subsonic diffusers. The model includes sufficient internal volume to accommodate a large number of ESP modules internally. Removable throat rakes with up to 30 total probes (+15 psid) would be accommodated on the parametrically interchangeable cowl lips, while use of a 4" engine face diameter allows use of an industry standard 40 total (+15 psid) and dynamic (2000 Hz) probe rake. Throttle-dependent drag forces can be measured by incorporating a six-component force balance at the strut-sting interface.

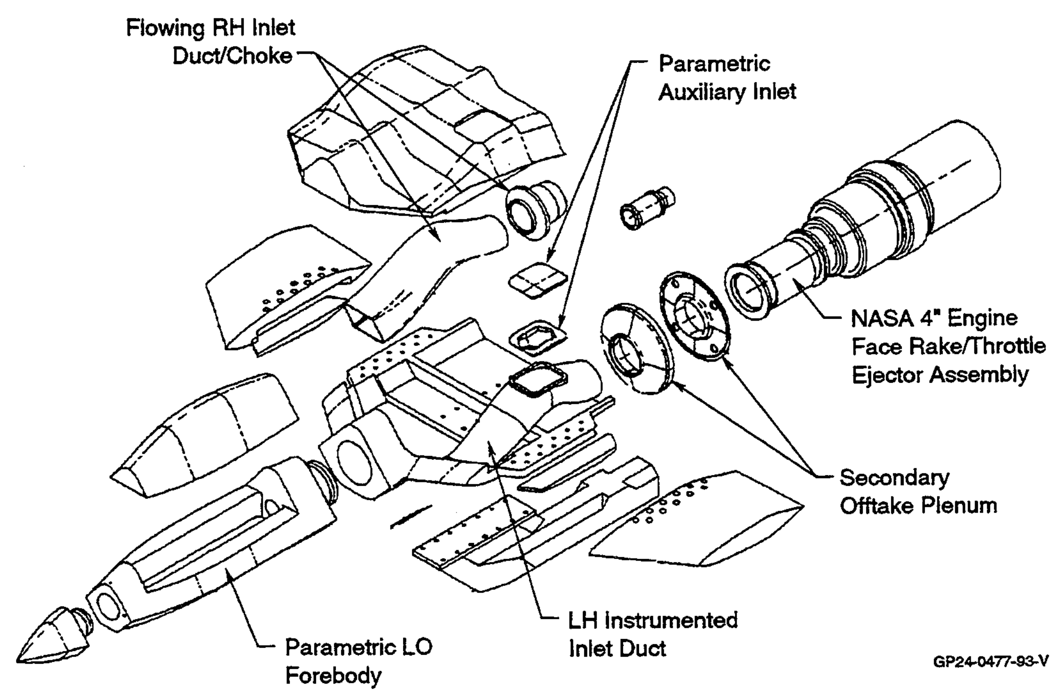

Figure 104. AMA 003 Integrated Inlet Model Concept
Trimetric

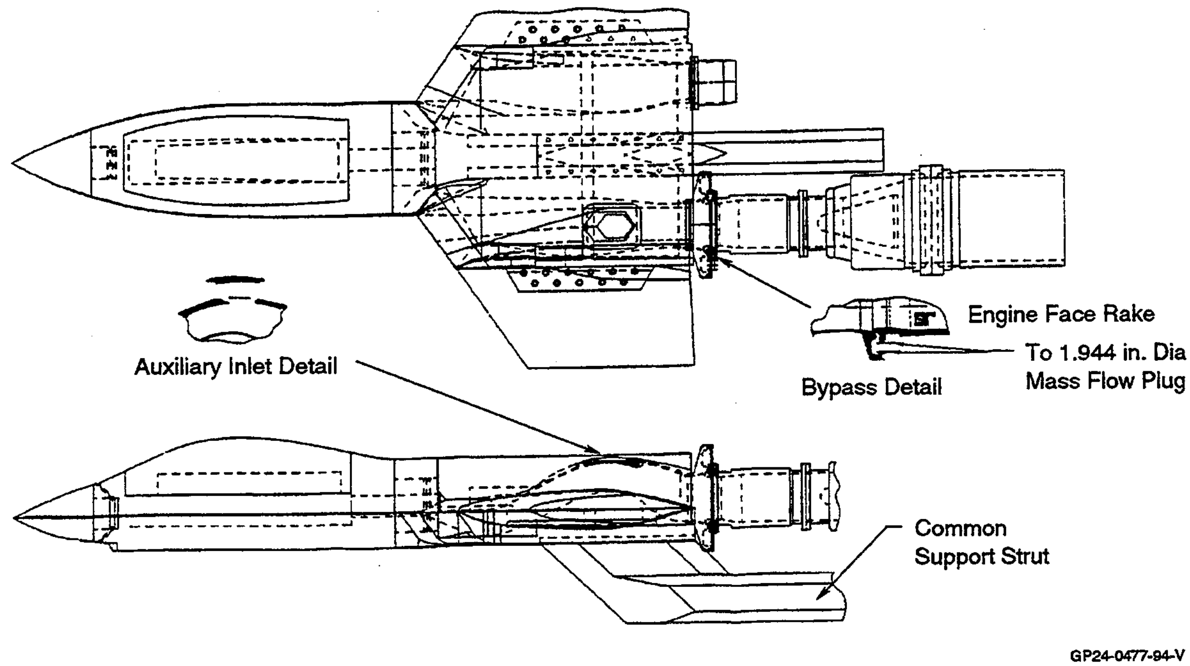

Figure 105. AMA 003 Integrated Inlet Model Concept
Plan and Sheer Views

Both the MRF 1209 and AMA 003 model concepts have been designed for test flexibility and fabrication simplicity, given the use of Computer-Aided Design (CAD) and Numerical-Control (NC) machining capabilities. Unigraphic CAD files for these model concepts have been fully "surfaced". Model detail design and stress analysis is estimated to require less than 1000 man-hours for both models. Because of the use of common hardware such as the small mass flow plugs, and strut support and the incorporation of existing NASA engine fall rake, mass flow plug, and model sting hardware, model fabrication is estimated at less than 4500 man-hours for both models.

5.0 CONCLUSIONS

The development of an inlet system for an advanced fighter or attack aircraft configuration must include consideration of the inlet design impact on inlet Radar Cross Section (RCS), weight and cost, as well as aerodynamic performance. Use of Quality Function Deployment (QFD) techniques are essential in the evaluation of an air induction system's design impact on a broad set of system "qualities". Use of QFD techniques can insure that a well-balanced design selection is made, but cannot completely displace design experience in selection, and only insures selection of a "local" optimum for the air induction system itself, not for the weapon system as a whole. Use of a more comprehensive QFD analysis of the entire weapon system is required to select a "global" optimum for the weapon system and integrated air induction system.

The set of inlet design features selected for the Multi-Role Fighter (MRF) Model 1209 and Advanced Medium Attack (AMA) Model 003 bomber weapon system concepts represent the best compromise between expert-weighted performance, signature, weight and cost figures-of-merit. These selections were not determined solely by performance as in previous studies of this type, but were strongly influenced by RCS, weight and cost considerations. Both concepts did, however, provide the smallest Takeoff Gross Weight (TOGW) penalties of the six configurations assessed.

Interrogation of the design database available to perform conceptual trade studies required for advanced air induction systems identified a number of database deficiencies which could benefit from more generic research. These deficiencies include a better understanding of the integrated performance (aerodynamic and RCS) of LO-configured forebody and inlet boundary layer management, integrated LO-inlet aperture aero performance at static and maneuvering flight conditions, bifurcated and serpentine subsonic diffuser RCS performance and material treatment effects, serpentine subsonic diffuser hammershock loads, secondary airflow system integration concepts, aerodynamic performance, weight and costs, and installed engine advanced front frame aerodynamic and RCS performance. Large-scale computational fluid dynamic analyses of the MRF 1209 and AMA 003 integrated inlet geometries confirm the viability of each configurations basic aerodynamic design, and the sensitivities of integrated inlet aerodynamic performance to inlet design integration details, such as cowl lip shape or fuselage camber. These sensitivities highlight the criticality of early, parametric inlet aerodynamic research, particularly on integrated effects.

Research to better understand these issues must be conducted in the context of technology availability dates (TAD's) for next generation weapon system concepts to maximize the benefits to government and industry. A timely and well-planned program aimed at the key issues identified in this study would provide an invaluable resource for future inlet designers.

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APPENDIX A – SUPERSONIC INLET SIZING PROCEDURES

The use of the inlet performance characteristics and the engine airflow specification to determine the necessary inlet capture area for external and mixed compression inlets is discussed below. The inlet airflow requirements at takeoff and low subsonic speeds are also briefly discussed.

A.1 EXTERNAL COMPRESSION INLETS

To define the size of a given inlet design, it is necessary to establish the airflow requirements for the entire propulsion system. With these airflow requirements, the inlet performance characteristics, and the required engine airflow the inlet capture, A_c, can be computed as follows.

For a typical external compression inlet operating subscritically, the airflows to be considered are (see Figure A-1):

- Engine airflow
- Engine compartment cooling (ECC) airflow
- Environmental control system (ECS) airflow
- Inlet bleed airflow
- Inlet duct leakage
- Inlet sidespill
- Inlet subcritical spill

These airflows are briefly discussed below. The basic sizing equation is derived, and the application of this equation to fixed and variable capture area inlets discussed.

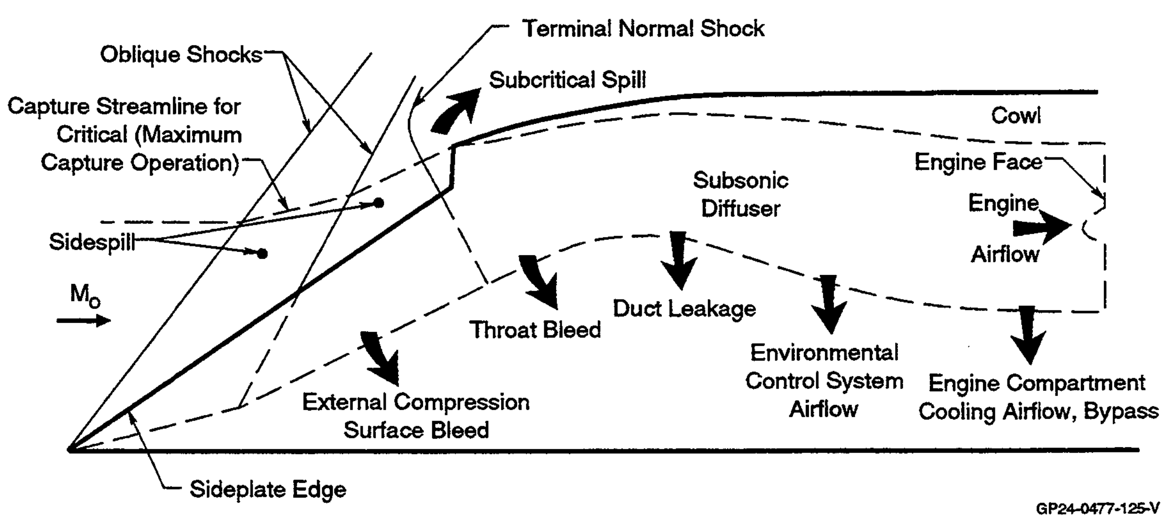

Figure A-1. Typical External Compression Inlet Airflow Schematic

A.1.1 Inlet Airflow Components

Engine Airflow and Engine Airflow Tolerance – Engine airflow is given by the engine manufacturers performance specification as a function of power setting, flight Mach number, altitude, and ambient temperature. The specification airflow is a mean value which varies from engine to engine because of manufacturing tolerance, etc. Therefore, a typical value of 1.5 percent is usually added to the engine airflow for sizing purposes.

Engine Compartment Cooling Airflow – An allowance, depending on the specific design, is normally made for the air which is taken from the air induction system to cool the engine compartment.

Environmental Control System Airflow – Air is usually supplied from a plenum in the subsonic diffuser to a heat exchanger to supply the vehicle environmental control system airflow. Typically, approximately 1 percent of the cowl lip station airflow is adequate for this purpose.

Inlet Bleed Airflow – The amount of boundary layer bleed is a strong function of the design being considered, and it is difficult to generalize insofar as the required amount is concerned. Typical Mach 2.0 inlet bleed schedules require between 3 and 8% of engine airflow. The F-18 C/D inlet bleed schedule is presented in Figure A-2 as an example.

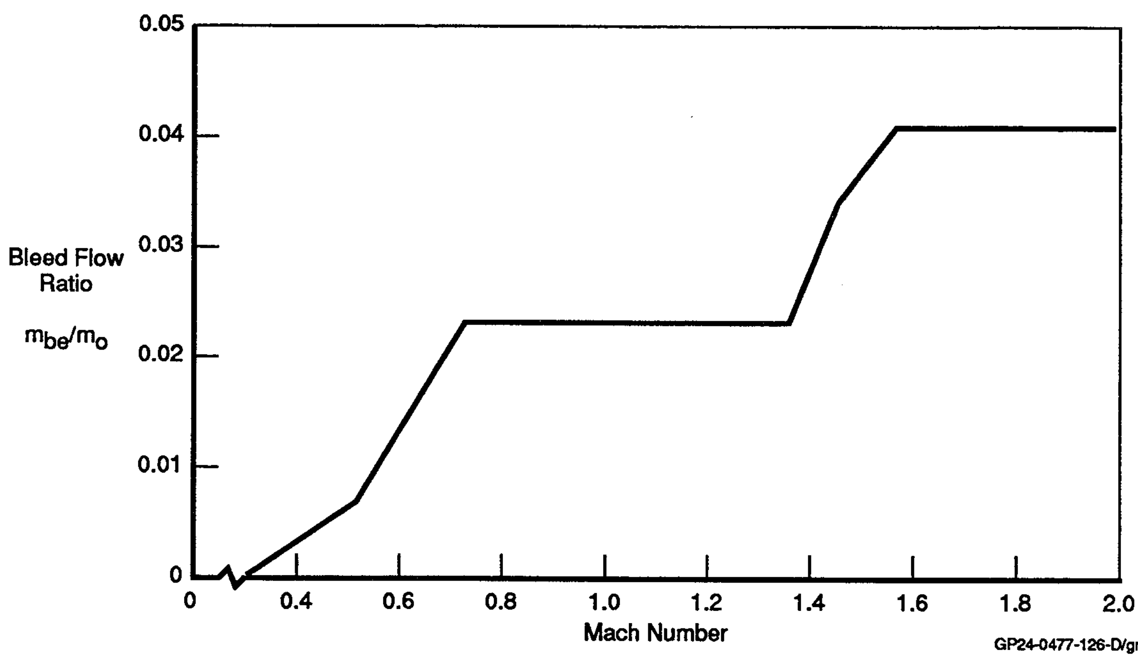

Figure A-2. F-18C/D Ramp and Throat Bleed Flow Ratio

Inlet Duct Leakage – Inlet duct leakage refers to the airflow lost in the compression process through hinges, seams, and in corners where the compression ramp meets the inlet sidewall.

Inlet Sidespill – Sidespill losses refer to the lateral spillage of air through the area bounded by the shock structure, the captured streamline, and the sideplate boundary.

Inlet Subcritical Spill – Subcritical spill refers to that airflow spilled subsonically behind the terminal normal shock. Operation with some subcritical spillage is generally desirable for low duct distortion and to allow for engine transient airflow changes. A typical value for this spillage is 3 to 5 percent of the airflow at the cowl lip station.

A.1.2 Inlet Sizing – The use of the inlet airflow components to derive the basic sizing equation is described below. Airflows are expressed in terms of their "equivalent freestream areas".

The sum of the engine dependent airflows is defined as the aifrlow required by the engine, that is

$$A_{o\,\substack{\text{required}\\\text{by angle}}} = A_{o\,\text{engine}} + A_{o\,\substack{\text{engine}\\\text{tolerance}}} + A_{o\,\substack{\text{engine}\\\text{angle}}} \tag{1}$$

The difference between the maximum (critical) streamtube of air captured by the inlet and the inlet dependent airflows is defined as the airflow available to the engine, that is

$$A_{o\,\text{available}} = \left[\frac{A_o}{A_{c_{\substack{\text{maximum}\\\text{capture}}}}} - \left(\frac{A_o}{A_{c_{\substack{\text{subcritical}\\\text{spill}}}}} + \frac{A_o}{A_{c_{\text{sidespill}}}} + \frac{A_o}{A_{c_{\text{bleed}}}} + \frac{A_o}{A_{c_{\substack{\text{environmental}\\\text{contol system}}}}} + \frac{A_o}{A_{c\,\substack{\text{duct}\\\text{leakage}}}}\right)\right] A_2 \tag{2}$$

The minimum inlet size is defined when these airflows are matched, that is, when

$$A_{o\,\text{available}} = A_{o\,\substack{\text{required}\\\text{by engine}}} \tag{3}$$

Substituting Equations (1) and (2) into (3) gives the basic sizing equation,

$$A_{o\,\text{required}} = \frac{A_{o\,\text{engine}} + A_{o\,\substack{\text{engine}\\\text{tolerance}}} + A_{o\,\substack{\text{engine}\\\text{angle}}}}{\left[\frac{A_o}{A_{c_{\substack{\text{maximum}\\\text{capture}}}}} - \left(\frac{A_o}{A_{c_{\substack{\text{subcritical}\\\text{spill}}}}} + \frac{A_o}{A_{c_{\text{sidespill}}}} + \frac{A_o}{A_{c_{\text{bleed}}}} + \frac{A_o}{A_{c_{\substack{\text{environmental}\\\text{contol system}}}}} + \frac{A_o}{A_{c\,\substack{\text{duct}\\\text{leakage}}}}\right)\right]} \tag{4}$$

A.1.3 Sizing Procedure For Fixed Capture Area (FCA) Inlets – For each flight condition (Mach number, altitude, angle of attack) in the flight envelope Equation (6) is used to compute the required inlet capture area. Note that the inlet performance and engine specifications must be known at each of these points. The largest of the required inlet capture areas is then the capture area necessary for the inlet. At the sizing point no bypass will be necessary. At other points the inlet will be larger than required and some spill or bypass will be necessary to match the duct airflow to that required by the engine. The maximum engine corrected airflow at the highest flight Mach No. occurs at the tropopause (11000 meters or 36089 feet pressure altitude), because engine airflow is usually scheduled as a function of TT2 or engine face total temperature. For this reason, inlet sizing is usually accomplished using engine airflow lapse at 36089 feet pressure altitude, on either standard or cold day atmospheric conditions.

A.1.4 Capture Requirements At Takeoff – After the inlet has been sized for supersonic flight, checks must be made at takeoff and low speed conditions to ensure that the throat is large enough to pass the required flow with a throat Mach number of 0.77 (95% critical airflow) or lower. Evaluation of the throat Mach number requires an estimate of the static inlet pressure recovery. If a reduction in throat Mach number at takeoff or low speed conditions is necessary, several methods may be used. These include increasing the throat area, providing for a variable geometry cowl lip section, or inclusion of auxiliary inlets which may be actuated or "blown-in" at takeoff.

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A conceptual design trade study was conducted by McDonnell Aircraft Company (MCAIR) and NASA LARC PAB to determine the impact of inlet design features incorporated for reduced detectability on inlet performance, weight, and cost, for both fighter and attack-type aircraft. Quality Function Deployment (QFD) techniques were used to prioritize trade study issues, and select "best" air induction system configurations for each of two notional aircraft, the Multi-Role Fighter (MRF) and the Advanced Medium Attack (AMA) bomber. Database deficiencies discovered in the trade study process were indentified, and technology roadmaps were developed to address these deficiencies. Finally, two high speed inlet wind tunnel model concepts were developed for follow-on wind tunnel investigations.

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